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Abstract

The objective of this project was to develop a relatively simple, yet accurate method for testing the envelope leakage rate of tall buildings. Alternative pressurization test techniques were developed and two methods, the floor-by-floor blower door method and the air handler method, were tested on two buildings. The floor-by-floor blower door method involves isolating and measuring the leakage flow rate through a single floor. Difficulty in eliminating inter-floor leakage in the floor-by-floor blower door method led to the development of the air handler method. In this method, air handler fans pressurize the whole building or a building zone using outdoor air. The outdoor air flow rate through the fan is measured using a tracer gas dilution technique with only one flow meter and one concentration sensor. The leakage characteristics of the test zone can then be calculated by establishing a relationship between the pressure differential across the building envelope and the corresponding outdoor air flow. The air handler method using a tracer gas flow measurement technique provides the most straightforward and efficient procedure to determine the leakage characteristics of tall buildings. It produced highly repeatable results with an estimated uncertainty of 5.5%.

The Pennsylvania State University

The Graduate School

Architectural Engineering Department

PROTOCOL FOR FIELD TESTING OF TALL BUILDINGS TO DETERMINE ENVELOPE AIR LEAKAGE RATE

A Thesis In

Architectural Engineering

by

Brian W. Lee

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

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1. Introduction

1.1 Background

Building envelope tightness is of importance to building owners, operators, and tenants for operational, indoor environmental quality and financial reasons. Skin leaks in buildings coupled with pressure differential due to stack effect and wind can cause several unwanted results.

A large stack effect pressure differential across building shafts can generate objectionable noise. This noise is particularly evident at stairwell and elevator doors, and is a major concern of building tenants. Envelope leakage can cause indoor air quality control problems by introducing unconditioned outdoor air into the building or by causing the transfer of contaminated air from one part of the building to another. The exfiltration of conditioned air can cause moisture problems if air is cooled below its dew point while travelling through an exterior wall. Comfort can also be reduced when outdoor air enters directly into a conditioned space. This infiltration adds to air conditioning loads and must be accounted for during mechanical system design to maintain satisfactory conditions in the space. A reduction in the envelope leakage can provide significant savings in both the capital cost of heating and cooling equipment and its associated operating costs.

Measurement of the envelope leakage of houses and other small buildings through pressurization testing is a common procedure. The test procedure requires a large fan to pressurize or depressurize the building. Once a steady state pressure differential is achieved between the building and its surroundings, the pressure differential and the air

flow rate into or out of the building are measured. A correlation between the air flow and the envelope pressure differential can then be found and are used to estimate the envelope leakage under a variety of conditions. In principle, this approach is also applicable to tall buildings. However, the magnitude of the stack and wind effects, not to mention the flow rates required for standard leakage tests, make transfer of these techniques to tall buildings less than straightforward.

1.2 Objective

The objective of this project was to develop a method to evaluate the airtightness of the exterior walls of tall buildings that represents the best compromise between simplicity and accuracy. Previous envelope leakage test methods were analyzed and new methods were developed based on the existing test techniques.

1.3 Scope

The scope of this project included: 1) a review and analysis of the published literature on envelope leakage, 2) the development of two envelope leakage test techniques, and 3) the measurement of leakage rates in two different buildings with the two techniques 4) an evaluation of the methods based on the following criteria: value of the information acquired, cost, and disruption of building operations.

2. Literature Review

2.1 Effects of Envelope Leakage on Building Performance

Infiltration accounts for approximately 20 to 60 percent of the building heating design load (Harrje et al. 1990; Persily and Grot 1986) and can lead to indoor humidity problems (Shaw et al. 1973; Tamura and Shaw 1976). Envelope leakage, in combination with internal leakage, is also responsible for the noise and odor transport problems caused by stack effect. Reducing infiltration can result in savings in the heating and cooling equipment capital costs and in the building operating costs.

A large contributor to the overall envelope leakage rate is fenestration leakage. Most window manufacturers certify that the window air leakage per unit of operable crack perimeter has been tested to be below 0.17 l/s·m (0.37 scfm/foot). However, this leakage rate has consistently been found to be on the order of 50 - 200 percent higher in independent tests (Kehrli 1995). Kehrli found that a two story building outfitted with windows permitting an air leakage rate of 0.24 l/s per meter of operable crack perimeter (0.50 scfm/ft), i.e. 37 percent greater than the nominal value, will have an increased operating cost of approximately five percent. The increased operating costs due to the additional window leakage will be even greater under the higher skin pressure differentials present in tall buildings. The additional leakage will cause higher peak heating and cooling loads resulting in increased capital cost of the heating and cooling equipment.

Envelope leakage can cause many other unwanted effects in building operation. A major concern from both a structural and an aerobiological perspective is the effect of moisture

in the exterior walls caused by exfiltrating air. The moisture content in the exterior walls has been shown to be dependent primarily on the relative humidity within the space coupled with the force of both exfiltration and thermally driven vapor pressure differences (TenWolde et al. 1995). Moisture accumulation in the wall air cavity creates a climate conducive to microbial growth.

The indoor-outdoor temperature differential creates air density differences, which cause the pressure changes commonly known as stack effect (ASHRAE 1997). As the outdoor air temperature falls below the indoor air temperature, the warm air within the building begins an upward flow pattern through small openings in the floor and in the vertical building shafts. The air exits near the top of the building and is replaced by cold outdoor air infiltrating at lower levels. In the summer months, when the outdoor temperature typically rises above the indoor temperature, the flow pattern is reversed; outdoor air infiltrates through the top levels of the building and exits through the bottom levels. The stack effect pressure differentials decrease in the warmer months because the indoor-outdoor temperature difference is smaller. Envelope leakage in a tall building, driven by stack effect, can lead to large pressure differentials across the building skin and promote inter-floor air movement. Building floors create a large resistance to flow and cause most of the internal air flow due to stack effect to travel through vertical shafts (Tamura and Shaw 1976).

Some of the problems caused by stack effect are:

1. the transportation of odors and other air pollutants;

2. noise, created by the air entering or escaping the vertical shafts through small openings around the stairwell and elevator doors; and
3. difficulty opening (or closing) outside or stairwell doors due to large pressure forces acting on them.

2.2 Envelope Leakage Measurement Techniques:

The goal of envelope leakage measurement techniques is to measure the envelope leakage accurately in the simplest and most cost-effective manner. A number of different envelope leakage measurement techniques are described in the literature. These include: the fan pressurization method (CAN/CGSB-149.15 1996; ASTM 1992); the use of buoyancy caused by stack effect to create pressurization (Hayakawa et al. 1990); and tracer gas techniques (Kronvall 1980). Each method has merits based upon its accuracy, cost effectiveness, and simplicity.

The leakage test methods reviewed involve the pressurization or de-pressurization of the test zone to force air through the building envelope. A correlation is developed between a series of steady state pressure differences across the test zone boundary and the corresponding air flows required to maintain that pressure differentials (Kronvall 1980). Published envelope leakage test techniques utilize a variety of methods to maintain the desired pressure differential within the test zone. The pressurization method coupled with the method of measuring the air flow traveling through the envelope are the distinguishing characteristics of envelope leakage test techniques.

The pressurization techniques used in previous test methods are:

1. the use of centrally located building fans, closing the return and exhaust air dampers, to pressurize the building (Shaw et al. 1973);
2. the use of a portable blower door to pressurize the test zone in the building (Hunt 1986; Modera 1995);
3. the use of a large fan (with a capacity large enough to alter the pressure in the entire building) outside the building that can be used like a blower door (Shaw et al. 1990); and
4. the use of stack effect to pressurize or depressurize the whole building (Hayakawa and Togari 1990).

Each of these methods either depends on the climatic conditions or requires special pressurization equipment, which may be costly. Additionally, each test method requires comprehensive understanding of both the testing equipment or the mechanical system in the building.

The two most commonly used classes of techniques for measuring leakage air flow rate are:

1. zone tracer gas concentration methods; and
2. fan air flow measurement methods.

The largest uncertainty in envelope leakage testing is associated with flow measurement. The total uncertainty depends upon a combination of uncertainties in the test apparatus accuracy, the inter-zonal air transfer (in methods that do not test the whole building simultaneously), and the assumptions made about air mixing (in tracer gas tests). To

reduce potential error in the envelope leakage testing procedure due to inter-zonal transfer, air flow between adjacent zones and the testing zone must be excluded.

Zone tracer gas concentration flow measurement techniques are used to measure the envelope leakage within the zone being tested. The three most widely used types of zone tracer gas concentration techniques are:

1. decay of tracer gas concentration;
2. constant tracer gas concentration; and
3. constant tracer gas emission.

Each of these techniques requires the release, capture, and monitoring of the tracer gas in the test zone. The three zone tracer gas concentration methods are discussed in further detail in Section 2.2.1.

The fan air flow measurement techniques measure the total air flow entering the test zone as it flows through the pressurization fan. This measurement through the pressurization fan is most commonly done using:

1. pitot tube traverse air flow measurement;
2. blower door air flow measurement; or
3. tracer gas dilution measurement.

The fan air flow measurement techniques are used with the premise that all air entering the pressurized space must be exiting through the exterior wall, i.e. that inter-zonal leakage is zero. This condition is probably never satisfied in reality, but if inter-zonal leakage can be kept small, the resulting error will remain within acceptable bounds. A

more detailed description of the fan air flow measurement techniques is provided in Section 2.2.2.

2.2.1 Zone Tracer Gas Concentration Measurement Methods

Zone tracer gas concentration test methods involve the injection of a detectable gas directly into the test zone, and recording of variations in the concentration of the gas over time. Each of the tracer gas concentration methods listed above uses an easily measured, non-toxic tracer gas that is not normally present within the building. Two of the most common tracer gases used for air flow measurement testing are N_2O and SF_6. A description of each of the zone tracer gas concentration methods follows.

1. *Decay of tracer gas concentration.* The decreasing tracer gas concentration leakage measurement technique is carried out by injecting a small quantity of distinguishable gas into the test zone. The tracer gas must be well mixed throughout the space before the pressurization/depressurization fans are activated. Without assisted mixing, a uniform concentration in the space can take up to 3.5 hours to achieve after the initial tracer gas injection. This can be reduced to 30-45 minutes with enhanced mixing (Sieber et al. 1993). Once the gas concentration within the space has become uniform, the pressurization fans are activated and the decreasing tracer gas concentration in the test zone is recorded as a function of time. The ventilation rate, assuming negligible interior air transfer, can be calculated as a function of the initial and final concentrations, time, and the test zone volume (Yoshino et al. 1995; Kronvall 1980). To avoid inter-zonal air transfer, the zones adjacent to the test zone must always be pressurized to the test zone pressure. This pressurization process may be difficult to control and will

introduce significant error into the results if the interior leakage is not reduced to a small fraction of the total leakage. For this reason, this method is often used to test small buildings and houses, which can be tested as a single zone.

The tracer gas concentration decay test is physically easy to perform, but accurate determination of inter-zonal air flow rates in large buildings can be difficult. The accuracy of the flow rate measurement, tested on a small, multi-room residential home without any inter-zonal air transfer, was calculated to be approximately 15 percent (Sandberg and Blomquist 1985). Factors affecting the accuracy of this method are the validity of perfect mixing assumptions and the accuracy of zone volume calculations. The tracer gas may not be perfectly mixed throughout the room or can become trapped in furniture, thereby decreasing the accuracy of the test results. Additionally, the internal volume of the test zone may be difficult to determine accurately, because the furniture in the space can occupy a large percentage of its gross volume.

2. *Constant tracer gas concentration.* The constant tracer gas concentration method entails discharging a distinguishable gas into the test zone at a flow rate controlled by a concentration sensor within the space. In the ideal case, the control device, activated by a concentration sensor, will automatically release the tracer gas into the room to keep the concentration level at a fixed value. The leakage rate is calculated by performing a steady state mass balance on the tracer gas in the test zone. Concentration is a function of both the tracer gas emission rate and the room volume. The advantage of the constant tracer gas concentration technique is

that it can yield in separate room flow rates through monitoring of tracer gas concentration change over time in multiple test rooms. The primary disadvantage is a more complicated and costly testing apparatus that requires additional labor and knowledge to perform accurate tests. Additionally, imperfect mixing of the tracer gas can cause delays in the zone concentration measurement introducing test error into the resulting flow rate.

3. *Constant tracer gas emission.* The constant tracer gas emission test is performed by injecting a constant flow rate of a distinguishable gas into the test zone. A tracer gas sensor records the concentration in the space over time. Given that the tracer gas injection rate and volume of the space are known, the measured tracer gas concentration in the space serves to indicate the air leakage rate. Assuming the tracer gas is well mixed in the test zone, the transient envelope leakage rate is calculated as follows (Lagus and Lie 1990).

$$Q(t) = \frac{F - V \cdot C(t)}{C(t)} \tag{2.1}$$

where,

V = Volume of the test zone (m^3)

C(t) = Concentration as a function of time (m^3/m^3)

Q(t) = Air leakage as a function of time (m^3/s), and

F = Source injection rate (m^3/s)

This method can be applied to either a transient or steady state process. The transient calculations introduce additional test error as a result of the assumptions

made about the mixing within the space. To eliminate this source of error, the constant tracer gas emission test is performed under steady state conditions. Assuming that the air flow rates remain constant for a sufficiently long period of time, then Equation 2.1 reduces to its steady state limit:

$$Q = \frac{F}{C} \tag{2.2}$$

Using equation 2.2, the air leakage rate can be calculated directly using the measured room concentration and the known tracer gas discharge rate. The advantages of this method include a simplified tracer gas apparatus and the ability to continuously monitor the leakage flow rate. A major disadvantage of the constant emission test is that it can take a longer period time for the space to reach steady state than the other tracer gas methods. The increased test time is dependent on the zone volume and the mixing efficiency within the zone, but can be on the order of two or three hours per test. Another disadvantage of this leakage test method is that it requires the release of a large amount of expensive tracer gas (Kronvall 1980).

Results of previous research indicate that a relatively high degree of flow measurement accuracy may be obtained with these tracer gas methods. Specifically, Sandberg and Blomquist (1985) calculated the uncertainty of the flow rate measurement in the zone tracer gas concentration measurement methods to range from 3.2 to 15 percent. However, the equipment cost, testing time, and expertise required to use them are significant disadvantages.

2.2.2 Fan Air flow Measurement Methods

Fan air flow measurement methods can be useful tools for calculating the envelope leakage air flow rate through a single zone, a whole building or an air handler zone. During envelope leakage pressurization tests, the air flow rate entering the test zone must be equal to the air flow rate traveling through the exterior wall, assuming that inter-zonal air transfer is zero. If the inter-zonal air flow is not zero, and if interior air flow paths have known characteristics, the envelope leakage air flow rate can be calculated by subtracting the known flow through the walls to adjacent zones from the total fan air flow rate. A whole building test may give a more accurate indication of the overall building leakage by eliminating the inter-zonal air transfer. However, the large air flow rate required to maintain a high pressure differential across the building envelope prevents this technique from being used in most large buildings. Therefore, the focus of this research has been on testing either an entire air handling zone or a smaller section such as a floor or group of floors within the building. This multiple zone testing approach can provide advantageous information about the distribution of leaks.

Testing the envelope leakage of an entire air handling zone requires the measurement of the air flow through a building ventilating fan. This is a common procedure often performed by the air balancing contractors. There presently exists a large volume of literature describing several common fan flow measurement test procedures. A widely used guideline is the Field Performance Measurements manual published by the Air Movement and Control Association, Inc. (AMCA 1976). This manual establishes guidelines to perform an accurate fan air flow measurement using the pitot tube traverse method. The pitot traverse is the most common fan flow measurement method, but there

exist other, less widely used techniques such as the blower door and tracer gas dilution methods. Brief descriptions of the pitot tube traverse, the blower door, and the tracer gas dilution air flow measurement methods are given below.

1. *Pitot tube traverse air flow measurement.* The pitot tube traverse is the most common method used for field measurement of supply and return fan flow rates. The pitot tube is essentially a pressure recording device that measures the difference between the total pressure and the static pressure in the duct. From this pressure difference and the air density, the air velocity in the duct can be calculated for a single point. The AMCA standards recommend that at least 25 velocity measurements be made in a grid pattern on a plane perpendicular to air flow in the duct (AMCA1976). The traverse plane should be selected along a duct segment of constant cross-section to ensure the straightness of the air flow. Subdivision of the duct into more, smaller areas will increase accuracy. In the grid pattern, each measurement should be taken in the middle of its associated area. After the velocity at each point on the grid has been determined, the flow rate can be calculated using the average pressure difference, temperature, and the cross sectional area of the duct. It is very important that there is a consistent flow pattern through each cross sectional area that is tested. A consistent flow pattern is defined by AMCA to be one in which 75 percent of the pressure measurements are at least one-tenth the maximum (AMCA1976). Often, this requirement cannot be satisfied due to deviations from uniform flow caused by system configuration. A substantial amount of testing time may be needed to satisfy the requirements of this method. However, if the guidelines are followed, an accuracy of 2 to 10 percent can be achieved (AMCA 1976; Lagus et al. 1991).

2. *Blower door air flow measurement.* The blower door is a self-contained measurement device that was designed specifically for airtightness tests. The blower door is placed either in an exterior doorway or in a window. Air is forced into or out of a zone at several measured flow rates and the induced pressure differential created in the zone is measured at each air flow rate. The blower door unit contains a powerful variable speed fan, which can be set up either to pressurize or depressurize a test zone. The blower door is equipped with either electronic or mechanical gauges that monitor the inside pressure, outside pressure, and flow rate through the fan.

   Blower doors can provide air flows of up to 23.6 m^3/s (50,000 cfm) (Shaw et al. 1990). The larger fan units sit on the back of a truck and are ducted directly to an exterior door. Only a few of these large fans are being used because they are costly and require a trained operator. Smaller fans have a maximum design air flow ranging from 2.1 m^3/s (4,500 cfm) to 3.1 m^3/s (6,500 cfm). These fans are easily set up in a doorway and can be carried to test locations. Unfortunately, the air flow through a single fan is often too small to conduct pressurization tests on large buildings. The accuracy of the blower door fan measurements is typically within 3 to 5 percent of the actual flow rate (Hunt 1986; Minneapolis Blower Door 1996), and the repeatability is from 0.4 to 1.0 percent (Upham, 1997).

3. *Tracer gas dilution measurement.* The tracer gas dilution technique is a third method to measure the air flow of building system fans. The tracer gas dilution method measures the volumetric flow rate by means of multiple concentration measurements. A tracer gas is injected into the duct at a constant flow rate. The concentration is then

measured at a point sufficiently far downstream to allow for thorough mixing. Assuming that the tracer gas has been perfectly mixed in the duct, the volumetric air flow rate is equal to the tracer gas supply flow rate divided by the difference in the upstream and downstream tracer gas concentrations.

$$Q = \frac{S}{C_D - C_U} \tag{2.3}$$

where,

Q = Volumetric air flow rate (m^3/s)

S = Tracer gas supply flow rate (ppm * m^3/s)

C_D = Tracer gas concentration downstream of the injection point (ppm), and

C_U = Tracer gas concentration upstream of the injection point (ppm)

This method is particularly advantageous when testing duct configurations that do not have long straight segments of constant cross-section to allow fully developed air flow. Changes in flow direction in the duct actually enhance the mixing of the tracer gas. However, uniform tracer gas dispersion throughout the air flowing in the duct may not be achieved and will decrease the accuracy in the results. If the gas is evenly dispersed throughout the duct, which can be enhanced with a distributed injection manifold, the accuracy has been proven to be within 1 to 3 percent of the actual flow (Lagus 1991).

3. Envelope Leakage Model

3.1 Theoretical Model of Envelope Leakage

Most envelope leakage test methodologies seek to obtain the data required to develop a model of the relationship between envelope air leakage rate and pressure differential across the exterior walls. This relationship is known to closely match the power law equation (ASHRAE 1997):

$$Q = C\Delta P^n \tag{3.1}$$

where,

Q	=	Air flow rate (m^3/s)
ΔP	=	Pressure drop across the exterior wall, ceiling, or floor (Pa)
C	=	Flow coefficient ($m^3/(s \cdot Pa^n)$)
n	=	Flow exponent (dimensionless)

The flow resistance is dependent upon the crack geometry, entering and exiting effects, and wall composition. Tests have shown that fixed size cracks with greater flow resistance tend to have a flow exponent, n, closer to 1. Conversely, large cracks that have little resistance to flow have an n value closer to 0.5. These are limiting values for cracks of fixed dimension. If cracks open or close under the influences of pressure differential, values outside this range may be obtained.

Equation 3.1 can be applied directly to an entire building only if the pressure differential across its envelope is essentially constant. However, tall buildings are subject to wind pressure and stack effect, which cause the pressure differentials across the building skin

to vary with height and wall orientation. To represent the leakage of a tall building with a variable envelope pressure differential with a single flow coefficient and exponent, Equation 3.1 can be generalized as follows:

$$Q = C\Delta P_{Avg}^{n} = C\frac{\sum_{i=1}^{M} A_i \Delta P_i^{n}}{A_{Total}} \tag{3.2}$$

where,

A_i = Wall "i" surface area (m^2)

ΔP_{Avg} = Average pressure differential (Pa) = $\left(\frac{\sum_{i=1}^{M} A_i \Delta P_i^{n}}{A_{Total}}\right)^{\frac{1}{n}}$

ΔP_i = Pressure differential across wall surface "i" (Pa) = $(P_{in}\text{-}P_{out})$

Note: Positive flow is assumed to be flow out of the building

Therefore, if $(P_{in}\text{-}P_{out}) < 0$, then $\Delta P_i^{n} = -\,[(\,|\,(P_{in}\text{-}P_{out})\,|\,)^{n}]$

M = Total number of surface areas in the zone.

The average pressure differential, ΔP_{Avg}, is the area-weighted, non-linear average of pressure over all surfaces of the envelope of the test zone. To solve for the flow coefficient and exponent in either Equation 3.1 or Equation 3.2, the building envelope flow rate must be measured at a series of pressure differentials. The equations can be solved for the two unknown values, C and n, with only two sets of pressure differential and the envelope leakage flow rate data. However, large uncertainty results with this method. Regression solutions based on many data sets can reduce the experimental error.

The flow coefficient and exponent values from Equation 3.1 or Equation 3.2 can be used to assess the overall building envelope leakage. Envelope leakage comparisons among tall buildings may be made by a number of methods, including:

1. Comparison of envelope leakage flow rate at a standard pressure differential across the envelope, calculated using Equation 3.1. A common comparison is to find the envelope leakage flow rate at a reference pressure of 50 pascals, (Q_{50}).
2. Direct comparison of C and n values.
3. Comparison of leakage area computed from flow rate and pressure differential. The effective leakage area, L, is the effective sum of the areas of all the openings in the building envelope calculated at some reference pressure. A common leakage area comparison is evaluated at a reference pressure, Δp_r, of 4 Pascals and is denoted as ELA_4 (Sherman and Palmiter 1995). The effective leakage area can be calculated as follows (ASHRAE 1997).

$$L = \frac{Q_r \left(\rho / 2\Delta p_r \right)^{0.5}}{C_D} \tag{3.3}$$

where,

L	=	Effective leakage area, (m^2)
Q_r	=	Predicted air flow rate at Δp_r, using C and n (m^3/s)
Δp_r	=	Reference pressure difference (Pa)
C_D	=	Discharge coefficient

A list of effective leakage areas for building components in low-rise apartment buildings is found in Chapter 25 of the ASHRAE Handbook of Fundamentals (ASHRAE 1997). The values are based on a reference pressure of 4 pascals and a discharge coefficient of 1.

4. Calculate the average air changes per hour at a standard pressure by dividing the calculated air flow rate at that pressure by the building volume.

All four methods described above are quite common methods of comparison. Methods 1, and 2 have been used to describe the envelope leakage of the buildings tested in this project.

There has yet to be a widespread effort to quantify the envelope leakage in tall buildings and detailed envelope leakage data is limited. Leakage coefficients for eight tall buildings obtained by Tamura and Shaw (1976) are summarized Table 3.1. Values of C_{Wall} in Table 3.1 are equal to C in Equation 3.1 and Equation 3.2 per unit wall area. There is a large variation in the C values, (0.20 to 1.12 $m^3/(s \cdot Pa^n)$), which indicates the wide range of tightness of the buildings. The n values, describing the nature of the envelope leakage cracks, also vary widely (0.50 to 0.75). This indicates that the envelope leakage in tall buildings is both variable and building specific.

Test Building	C_{wall} (cfm/ft^2*(in. H_2O)^n)	n_{wall} (dimensionless)
A	1.12	0.70
B	0.69	0.50
C	0.62	0.75
D	0.76	0.65
E	0.48	0.50
F	0.30	0.50
G	0.84	0.65
H	0.20	0.50

Table 3.1 - Experimental Flow Coefficient and Exponents
(Shaw and Tamura, 1976)

3.2 Limitations of the Envelope Leakage Model

After data from pressurization tests has been fitted to the power law equation (Equation 3.1 or 3.2), the resulting flow coefficient and exponent can be used to estimate the

leakage rate or effective leakage area at a specified pressure differential. Because they are based on measurements, these leakage predictions are subject to uncertainty. Uncertainty can be introduced by any of the following measurement and test parameters:

1. wind pressure effects on the measured pressure differential (Modera and Wilson 1990);
2. low and high pressure differential (Sherman and Palmiter 1995); and
3. extrapolation to the ELA_4 differential of four Pascals of correlations based on measurements at larger pressure differentials (Persily and Grot 1985).

The following sections will quantify the errors associated with these parameters, and then propose guidelines that will limit the uncertainty of each parameter.

Wind Pressure Error

Airflow around buildings can influence the envelope pressure differential and increase the overall uncertainty of the measured leakage rate values. The flow patterns cause the surface pressures to vary in both the vertical and horizontal directions across the face of a building. Pressure is measured at a relatively small number of points, from which an appropriate average, both spatial and temporal, must be computed. Error in this procedure can create scatter in the measured pressure differentials across the building envelope. This increases the uncertainty of envelope leakage or effective leakage area estimates (Modera and Wilson 1990).

Data published in the ASHRAE Handbook of Fundamentals quantifies the effect of wind pressure on the surface of the building (ASHRAE 1997). This information is useful as a basis for establishing the number and location of pressure taps for pressurization tests.

The following analysis will estimate the uncertainty in using from one to nine, evenly spaced pressure taps per exposure to measure the average pressures on the exterior of a building of square plan shape. The uncertainty associated with the following two building orientations was investigated: normal, and 30 degrees from normal to the prevailing wind. The building orientations were chosen because the surfaces that comprise them represent the full range of C_p distributions, from nearly symmetrical to very asymmetrical.

The pressure at a point on a building surface is the sum of the ambient and wind pressures. The wind pressure is a function of the wind direction, building shape, wall orientation, wind speed and air density. The building shape and wall orientations with respect to the wind determine the local pressure coefficient, C_P. Figure 4 in Chapter 15 of the ASHRAE Handbook of Fundamentals displays local pressure coefficient contours over the face of a tall building for 13 wall orientations, from 0 to 180 degrees (ASHRAE 1997). These contours can be used to calculate the local outdoor wind pressure at any location on the building surface, i.e.:

$$P_{Wind} = C_P \frac{\rho_a U_H^2}{2} \tag{3.4}$$

where,

P_{Wind} = Local wind pressure on the building surface (Pa)

C_P = Local pressure contours (dimensionless)

ρ_a = Outdoor air density (kg/m^3)

U_H = Approach wind speed at upwind wall height, H (m/s)

Uncertainty in the pressure measurement was analyzed by investigating the error in leakage flow rate to the n^{-1} power. The total leakage flow rate was calculated by the area-weighted combination of the pressure readings across the four faces of the building.

The horizontal distribution of pressure coefficients for each wall orientation of the two buildings was approximated by a polynomial expression obtained by regression of data digitized from the ASHRAE figures (ASHRAE 1997). A graph showing each of these functions for a building orientation (30 degrees from the normal to the prevailing wind direction) is shown in Figure 3.2. The local pressure coefficient for each pressure tap was calculated from the regressed equations, based on the location of the pressure tap as a percent distance across the face.

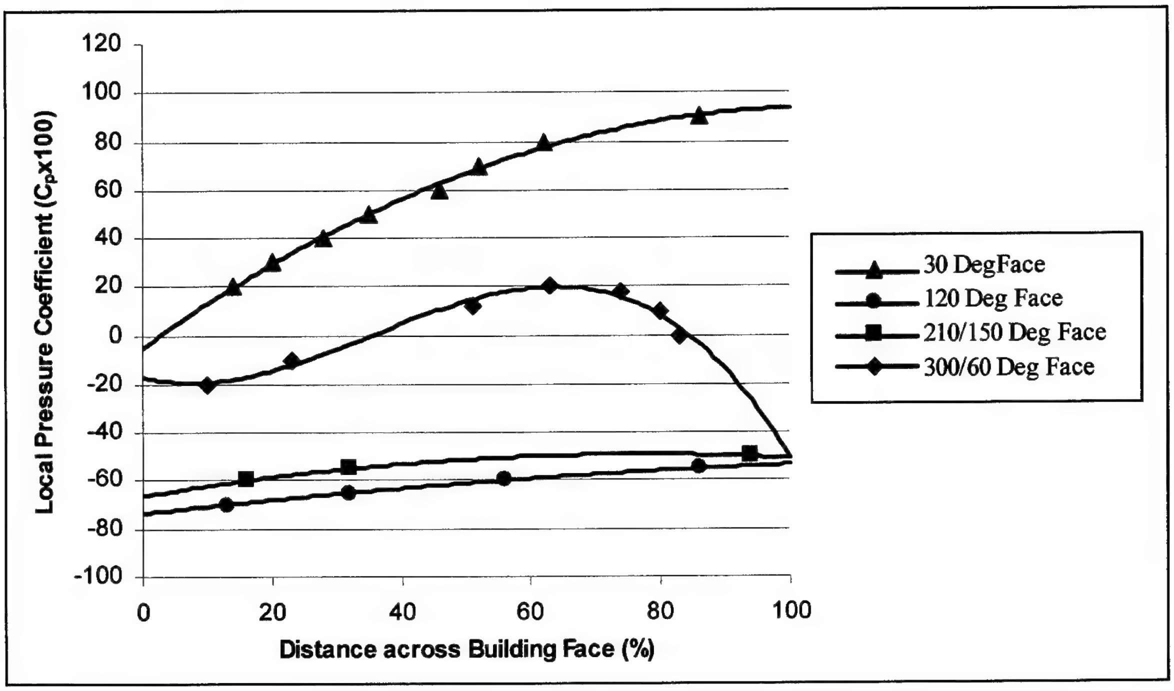


Figure 3.1 - Local Pressure Coefficients Functions for 4 Wall Orientations
The local pressure coefficients are displayed as a function of the distance across the building face. The wall orientations shown in the above figure represent a building with walls oriented 30, 120, 210, and 300 degrees from the normal to the prevailing wind.

Both "exact" and "measured" pressure differentials were determined for wind velocities ranging from 2 to 20 m/s. The "exact" pressure differential values for each exposure was calculated by integrating the difference between the indoor pressure and the regressed polynomial expression for each exposure from 0 to 100 percent. The "measured" values were calculated by area weighting the differential pressure tap measurements and are referred to as ΔP_{Avg} in the following equation.

$$\Delta P_{Avg} = \left(\frac{Q}{C}\right)^{\frac{1}{n}} = \left(\frac{\sum_{i=1}^{M} A_i (P_{in} - P_{wind})^n}{A_{Total}}\right)^{\frac{1}{n}} \tag{3.5}$$

where,

P_{in} = Indoor Pressure (12.5 or 50 Pa)

P_{Wind} = Local wind pressure on the building surface, from Equation 3.4 (Pa)

Note: Positive flow is assumed to be flow out of the building

Therefore, if $(P_{in}\text{-}P_{Wind}) < 0$, then $\Delta P_i^n = -\left[\left(\left|(P_{in}\text{-}P_{Wind})\right|\right)^n\right]$

The "measured" pressure differentials were dependent on the number and location of pressure sensors on each building face. Indoor pressures were arbitrarily chosen to be 12.5 and 50 Pascals. The flow coefficient remained constant and the flow exponent was assumed to be 0.6 for this analysis. Flow rates (Q/C) for each wall orientation were calculated by raising the "exact" and "measured" pressure differentials to the n^{th} power. A representative value of 0.6 was used in this example. The total leakage flow rate per building zone was calculated by adding the four wall flow rates. The resulting flow rates for a single building orientation, 30 degrees from the normal to the wind, is shown in Figure 3.3.

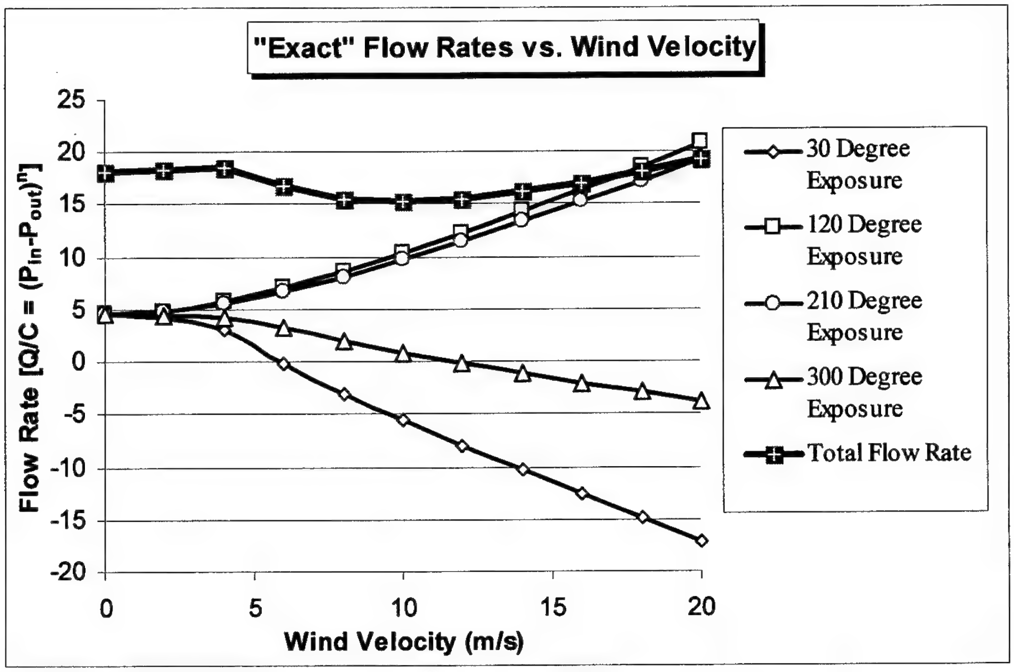


Figure 3.2 - The Effect of Wind Velocity on Leakage Flow Rates
The flow rates (Q/C) are displayed above as a function of the wind velocity. Positive flow rates are exiting the building. The total flow rate has a minimum at 10 m/s and increases linearly thereafter.

The total flow rates for both the "exact" and "measured" values were raised to the n^{-1} power, which results in the average pressure differentials. A percent error in the resulting "measured" average pressure, P_{Avg}, was calculated by the root mean square method for one to nine pressure taps per side. Tables 3.2 and 3.3 show the results of this analysis for a building oriented normal to the prevailing wind direction with indoor pressures of 50 and 12.5 Pascals, respectively. Table 3.4 displays the error resulting from a building oriented 30 degrees from the normal to the prevailing wind and an indoor pressure of 12.5 Pa.

Normal to the Prevailing Wind		Number of Pressure Taps								
		1	2	3	4	5	6	7	8	9
Wind Velocity (m/s)	2	0.11	0.03	0.01	0.01	0.01	0.00	0.00	0.00	0.00
	4	0.47	0.12	0.05	0.03	0.02	0.02	0.02	0.01	0.01
	6	1.25	0.28	0.13	0.08	0.06	0.04	0.04	0.03	0.03
	8	3.02	0.55	0.26	0.16	0.11	0.08	0.07	0.06	0.05
	10	13.37	1.58	0.05	1.09	0.42	0.06	0.39	0.17	0.07
	12	11.08	5.85	3.79	2.22	0.74	0.74	0.43	0.14	0.09
	14	7.57	2.92	1.53	0.88	0.51	0.27	0.10	0.02	0.12
	16	7.14	2.72	1.50	0.98	0.70	0.54	0.43	0.36	0.31
	18	6.81	2.47	1.32	0.85	0.61	0.46	0.38	0.32	0.28
	20	6.64	2.34	1.24	0.79	0.56	0.43	0.35	0.29	0.26

Table 3.2 - Percent Error in Pressure Measurement (0 Degrees and 50 Pa)

The percent error displayed in the table above is representative of a building oriented perpendicular to the prevailing wind. The indoor pressure was constant at 50 Pascals.

Normal to the Prevailing Wind		Number of Pressure Taps								
		1	2	3	4	5	6	7	8	9
Wind Velocity (m/s)	2	0.46	0.11	0.05	0.03	0.02	0.01	0.01	0.01	0.01
	4	3.00	0.54	0.24	0.14	0.09	0.07	0.05	0.04	0.03
	6	11.08	5.85	3.79	2.22	0.74	0.74	0.43	0.14	0.09
	8	7.09	2.66	1.44	0.92	0.64	0.48	0.37	0.30	0.25
	10	6.57	2.27	1.16	0.71	0.49	0.36	0.27	0.22	0.18
	12	6.43	2.15	1.09	0.66	0.45	0.33	0.25	0.20	0.17
	14	6.38	2.09	1.05	0.64	0.43	0.32	0.24	0.20	0.17
	16	6.36	2.06	1.03	0.62	0.42	0.31	0.24	0.19	0.16
	18	6.35	2.04	1.02	0.61	0.42	0.31	0.24	0.19	0.16
	20	6.35	2.03	1.01	0.61	0.41	0.30	0.24	0.19	0.16

Table 3.3 - Percent Error in Pressure Measurement (0 Degrees and 12.5 Pa)

The percent error displayed in the table above is representative of a building oriented perpendicular to the prevailing wind. The indoor pressure was constant at 12.5 Pascals.

30 Degrees to Normal to Wind		Number of Pressure Taps								
		1	2	3	4	5	6	7	8	9
Wind Velocity (m/s)	2	0.34	0.47	0.24	0.14	0.09	0.06	0.04	0.03	0.03
	4	0.88	1.99	1.05	0.58	0.36	0.24	0.17	0.13	0.10
	6	6.53	4.95	7.31	2.03	0.05	0.69	0.38	0.49	0.09
	8	3.25	17.69	2.12	4.95	4.15	2.56	2.26	1.28	1.10
	10	3.34	20.28	6.35	4.25	1.13	3.49	2.07	3.23	2.24
	12	13.22	20.61	9.82	8.02	1.38	1.93	1.03	1.91	1.35
	14	33.39	20.67	16.08	8.17	7.95	1.61	2.43	0.70	1.92
	16	38.91	20.69	17.26	7.87	8.62	3.90	2.87	0.32	1.25
	18	42.40	20.72	17.82	7.61	8.65	4.19	4.57	2.31	0.90
	20	44.91	20.78	18.12	7.44	8.53	4.62	4.60	4.51	1.23

Table 3.4 - Percent Error in Pressure Measurement (30 Degrees and 12.5 Pa)

The percent error displayed in the table above is representative of a building oriented 30 degrees from the normal of the prevailing wind. The indoor pressure was constant at 12.5 Pascals.

An analysis of the results indicates that under low wind speed conditions, the total number of pressure taps has little effect on the uncertainty in the measurement. However,

when wind velocity is greater than or equal to 4 m/s, the percent error is substantially less when using additional pressure taps. Additional concerns arise as the wind velocity approaches 4 m/s, such as the possibility of infiltration on the windward side of the building and large pressure gradients throughout the test zone. Therefore, the authors recommend the maximum wind velocity for envelope leakage testing be 4 m/s. The number of pressure sensors per exposure should be selected to accurately represent outside pressure effects on the differential pressure. Figures 3.2, 3.3, and 3.4 provide a technique to estimate the error in the pressure for a specific building zone and are not universal in nature. The trends indicate that using three or more sensors will result in less than approximately 1% error in the pressure measurement.

Low and High Pressure Differential Error

Use of data sets with low envelope pressure differentials could result in higher uncertainty in the overall leakage values. This phenomenon is a result of the uncertainty in the pressure measurements made over the range of low pressures. The pressure measurements made at low pressures may introduce large error into the envelope leakage model. To avoid misrepresenting the leakage characteristics of a building weighting factors are applied to present a more accurate fit to the power law equation, Equation 3.1. Likewise if the pressure measurements are made at too high a pressure, uncertainty resulting in departure from the power law equation may occur (Sherman and Palmiter 1995). To prevent both of these problems, the authors recommend that all testing be performed with interior-exterior pressure differentials from 12.5 to 75 Pa, as prescribed by ASTM Standard E779 (ASTM 1992). Additionally, the target pressures of the

the pressurization test (also adopted from the ASTM Standard E779) should be: 12.5, 25, 37.5, 50, 62.5, 75 Pascals.

Extrapolation Error

Large error can rise as a result of extrapolating a regression equation beyond the bounds of the measured data from which is was derived. It is common practice to describe the air leakage rate through a building envelope in terms of effective leakage area, ELA_4, as described by Equation 3.3. This measurement allows the comparison of different buildings under "atmospheric" conditions. However, research has shown that the highest uncertainties occur when extrapolating down to 4 pascals and are smallest in the middle of the range of measured pressure differences (Persily and Grot 1986).

In order to avoid this additional uncertainty, the authors recommend that tall building analysis be based on a comparison of the airflow per unit area of envelope at a measured pressure differential of 50 Pascals (Q_{50}/Area). This proposed procedure uses the flow coefficient and exponent solved for with regression analysis, but eliminates error caused by extrapolation as 50 Pascals is nearly centered within the testing limits of the pressurization test.

4. Test Methods

4.1 Introduction

The field testing of tall buildings to determine the envelope air leakage rate presents a variety of complications that are not present in houses or small buildings. These include but are not limited to: a larger envelope surface area, stack effect, and increased wind pressure. Two envelope leakage test methods with the potential to overcome these obstacles have been developed and tested: the floor-by-floor blower door method and the air handler method.

The floor-by-floor blower door method determines the leakage of zones spanning a single floor. Internal leakage paths within the building are sealed and the floors are pressurized with blower doors. This method is described in further detail in Section 4.2. The air handler method measures the envelope leakage through each air handler zone. This method utilizes the building supply or return fans that are centrally located in the mechanical room to pressurize the air handling zone. A detailed description of this method is found in Section 4.3.

4.2 Floor-by-Floor Blower Door Method

The floor-by-floor blower door test procedure is intended to isolate a selected floor of a building and determine the envelope leakage rate associated with that floor. It uses blower doors to pressurize the test floor and adjacent floors. A schematic of a typical floor-by-floor blower door test is shown in Figure 4.1. Air flow rates are indicated by the symbol Q and pressures by the symbol P.

The test floor pressure is maintained by a blower door fan or fans operated by a manual controller. Some blower door units are equipped with a data acquisition system that digitally records the entering air flow and the pressure in the space. The blower door can be installed either in a door from a stairwell shaft or mounted directly to an existing opening to the outside, such as an operable window.

If only the test floor is pressurized, there will be leakage to the adjacent upper and lower floors and it will be impossible to separate envelope leakage from inter-zonal transfer. Inter-zonal leakage (flows Q_{Up} and Q_{Down} in Figure 4.1) can be eliminated if the floors above and below the test floor are pressurized so that pressures P_{Up}, P_{Down}, and P_{Test} are equal. This requires a minimum of two additional blower doors or the use of the air handling unit fan can be controlled to achieve this same result. Under these conditions, the fan flow rate, Q_{Fan}, and the envelope leakage rate, Q_{Out}, are equal, when corrected to standard temperature and pressure (i.e., the mass flows they represent are equal).

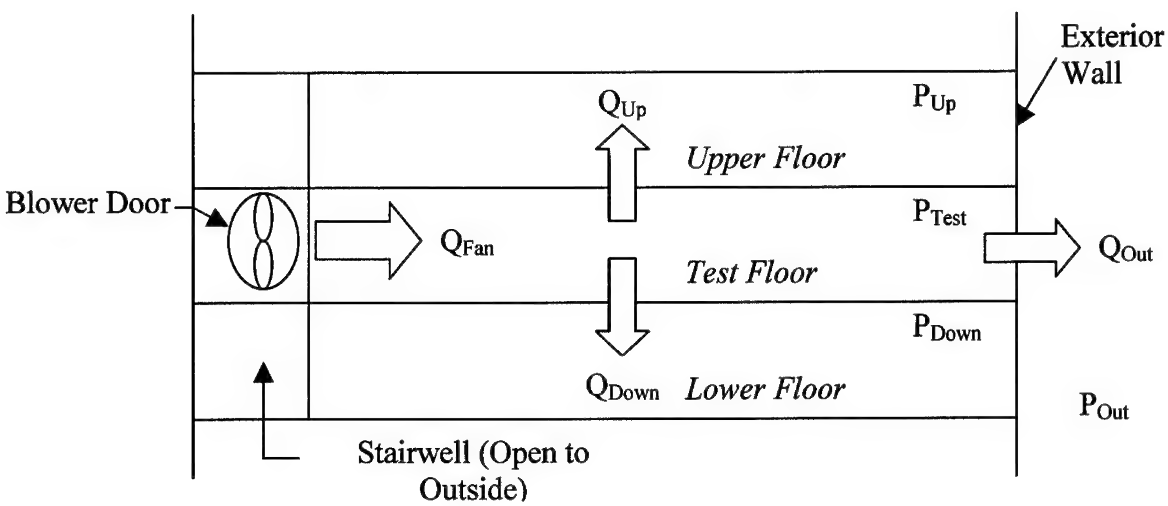


Figure 4.1 – Floor-by-floor blower door Testing Method Schematic

The major potential advantage of using this testing method in tall buildings is that one can determine the floor-by-floor distribution of envelope leakage. The ability to pinpoint areas of large envelope leakage would be an asset when determining which wall areas should be retrofitted given a limited budget. A logistical advantage of this procedure is that the leakage test can be set up on the unoccupied floors of an occupied building. As a result, testing can be performed without disrupting occupied floors as tenants periodically vacate their leased premises. This is a valuable advantage over other test methods that require the entire building (or large portions of it) to be evacuated. Also, test equipment is available that measures the entering air flow extremely accurately and easily, storing all data on a portable notebook computer. A single system operator rather than a group of testers can complete all data collection using this equipment.

The major disadvantage of this testing method is the set up time. Interior leakage paths from the testing floor to all other building components (such as elevator/stair shafts, ductwork) must be sealed. This can be a monumental task in the large buildings, since there can be many vertical shafts through a single floor. On an unoccupied floor, these leakage paths can be sealed during the day and remain sealed throughout the duration of the testing. If an occupied floor is to be tested, the sealing must be completed at night or on the weekend before the floor is tested, then removed before it is occupied again.

4.2.1 Testing Procedure

This section summarizes the major steps in the floor-by-floor blower door method testing procedure. This method is described in full detail in Appendix A-1.

1. Seal all interior leakage paths, including elevator shafts, stairwells, exhaust grilles,

and duct penetrations using non-permeable plastic sheeting and adhesive tape.

2. Open all interior doors (excluding stairwell doors) on both the test floor and the adjacent floors to increase the likelihood of a uniform pressure across the floors.
3. Set up a blower door either in a door leading from the test floor to a stairwell shaft that is open to the outside, or in a window on the test floor.
4. Lay out equally spaced pressure taps across each exterior face of the test floor and the two adjacent floors. Each pressure tap should be installed at the mid-height of the floor being tested.
5. Adjust the blower to maintain the desired pressure differential across the test floor envelope, 12.5 to 75 Pascals.
6. Pressurize the adjacent floors, using additional blower doors or an existing air handling unit, (Figure 4.2). Pressurizing the adjacent floors will eliminate all air flow through the floor and ceiling of the test floor. Sealing the interior flow paths on the adjacent floors may help increase the pressure on those floors. If pressure equalization cannot be attained, low accuracy is likely to result and the other leakage test technique described in this report should be employed.
7. Measure the pressure differential across each face of the building on the test floor and across the floors directly above and below. The pressure measurements must be repeated over a three-minute time period to average out the effects of large pressure fluctuations due to wind gusts.
8. Zero the pressure differential across the floor and ceiling of the test zone to minimize inter-zonal leakage.

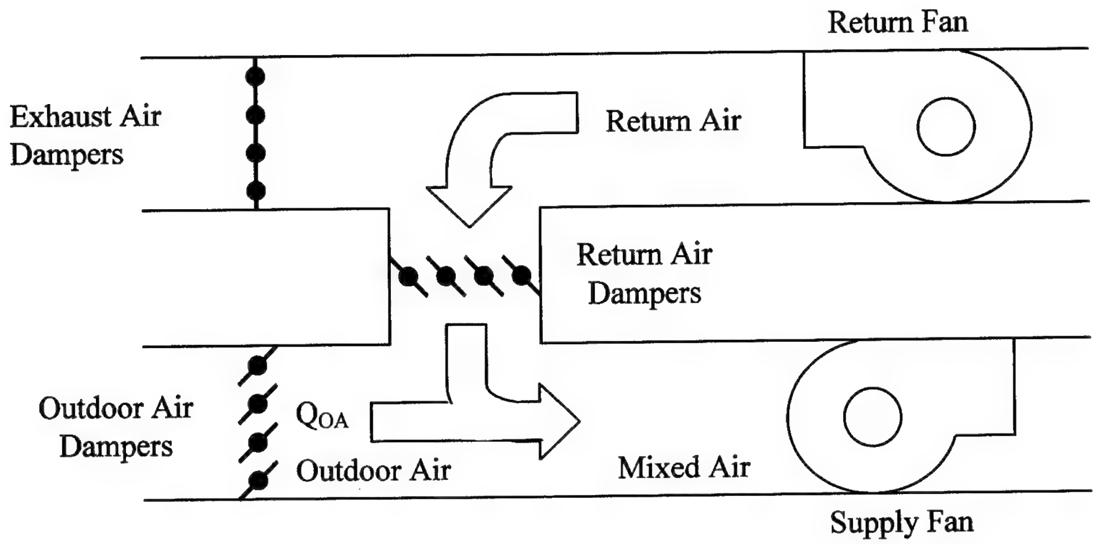


Figure 4.2 – Typical Air Handling Unit

Note: To maintain a fixed pressure in the space, close and seal the Exhaust Air Dampers and modulate the Return and Outdoor Air Dampers. This can be done by adjusting the set point temperature of the mixed air.

9. Run the pressure differential on the test floor through a series of values and measure the flow rate at each pressure. Each time the test floor pressure differential is changed, the pressure differential on adjacent floors must also be changed to match. To avoid including excessive uncertainty in the results the target test pressure differentials should be 12.5, 25, 37.5, 50, 62.5, and 75 Pascals, following the guidelines established by ASTM Standard E779 (ASTM 1992).

A complete analysis of the building envelope leakage rate requires the combination of the test results over a range of floors as described in the following section.

4.2.2 Leakage Rate Analysis

The data from a blower door method pressurization test are sets of pressures for the test floor, adjacent floors, and outdoors (P_{Test} ,P_{up}, P_{Down}, P_{Out}) and the corresponding air flow (Q_{Fan}) to the test floor. These data can be used to determine the flow coefficient and

exponent of a leakage model incorporating the known leakage paths: envelope leakage and inter-zonal air transfer to the upper and lower neighbor floors. In general,

$$Q_{Fan} = C_{Wall} \frac{\sum_{i=1}^{M} A_i \Delta P_{Test,i}^{n,wall}}{A_{Wall}} + C_{Up} \frac{\sum_{i=1}^{M} A_i \Delta P_{Up,i}^{n,up}}{A_{Up}} + C_{Down} \frac{\sum_{i=1}^{M} A_i \Delta P_{Down,i}^{n,down}}{A_{Down}} \tag{4.1}$$

where,

Q_{Fan} = Air flow entering the testing floor, measured by the blower door (m^3/s)

C_{wall} = Flow coefficient of the testing floor exterior wall ($m^3/(s \cdot Pa^n)$)

C_{Up} = Flow coefficient of the test zone ceiling ($m^3/(s \cdot Pa^n)$)

C_{Down} = Flow coefficient of the test zone floor ($m^3/(s \cdot Pa^n)$)

A_i = Wall "i" surface area (m^2)

A_{Wall} = Total test floor envelope area (m^2)

A_{Up} = Total floor envelope area on floor above test floor (m^2)

A_{Down} = Total floor envelope area on floor below test floor (m^2)

n, wall = Flow exponent of the testing floor exterior wall

n, up = Flow exponent of the test zone ceiling

n, down = Flow exponent of the test zone floor

$\Delta P_{Test,i}$ = $P_{Test} - P_{Out}$ (Pa), if $(P_{Test}-P_{Out}) < 0$, then $\Delta P_i^n = -[(|(P_{Test}-P_{Out})|)^n]$,

$\Delta P_{Up,i}$ = $P_{Test} - P_{Up}$ (Pa), if $(P_{Test}-P_{Up}) < 0$, then $\Delta P_i^n = -[(|(P_{Test}-P_{Up})|)^n]$,

$\Delta P_{Down,i}$ = $P_{Test} - P_{Down}$ (Pa), if $(P_{Test}-P_{Down}) < 0$, then $\Delta P_i^n = -[(|(P_{Test}-P_{Down})|)^n]$,

In the desirable case in which there is no inter-zonal air transfer, Equation 4.1 reduces to:

$$Q_{Fan} = C_{Wall} \frac{\sum_{i=1}^{M} A_i \Delta P_{Test,i}^{n,wall}}{A_{Wall}} \tag{4.2}$$

which is identical to Equation 3.2. In Equation 4.2, positive flow is assumed to be flow out of the building, therefore, if $(P_{in}-P_{out}) < 0$, then $\Delta P_i^n = -[(|(P_{in}-P_{out})|)^n]$. In this case, as few as two data sets are required to obtain estimates of C_{Wall} and n_{Wall}. However, it is imperative that additional pressure and air flow measurements are recorded, as a regression analysis will lead to a more accurate estimate (Sherman and Palmiter 1995). Leakage model coefficients can be calculated using a least squares analysis by minimizing the squared error of the predicted leakage rate relative to the measured leakage rate, i.e.,

(4.3)

$$Error = \sum_{i=1}^{N} [Q_{F,i} - Q_{F,Pred}]^2 = \sum_{i=1}^{N} [Q_{F,i} - C\Delta P_{Avg}^n]^2 \tag{4.3}$$

where,

$Q_{F,i}$ = Measured air flow rate (m^3/s)

$Q_{F,Pred}$ = Predicted air flow rate using Equation 3.2 (m^3/s)

The method of using a standard least squares fit to determine the leakage rate characteristics was adopted from ASTM Standard E779 (ASTM 1992). The Canadian standard addressing the fan pressurization method, CAN/CGSB-149.10-15-96, suggests including weighting factors for the exponential fit in the regression analysis. While noting the rigorous basis of the Canadian Standard, the authors have elected to conform with the ASTM procedure.

The following example illustrates the analysis of sample blower door test data. Sample test data are shown in Table 4.1. The pressures on the adjacent floors, denoted as P_{up} and P_{Down}, remain relatively constant as the pressure on the test floor, P_{test}, changes. A small pressure increase may occur on the adjacent floors as the test floor pressure rises because less air is moving from these floors to the test floor. Figure 4.3 shows the graph of the sample test data results tabulated in Table 4.1. Because data are available for cases with adjacent floor pressures both above and below the test floor pressure, interpolation can be used to pinpoint the air flow rate for which the pressure on the test floor is equal to the adjacent floor pressures ($\Delta P_{Floor} = 0$), thereby eliminating error due to inter-zonal transfer.

Sample Test Data			
Test No.	Q_{test} (m^3/s)	ΔP_{test} (Pa)	$\Delta P_{up}/\Delta P_{Down}$ (Pa)
1	530.4	35.6	50.0
2	1319.0	42.3	50.2
3	2383.3	48.6	50.0
4	3057.3	50.2	49.8
5	4156.8	56.0	49.9
6	4535.8	59.0	50.2
7	4919.8	62.0	50.0

Table 4.1 - Sample Blower Door Test Data

The blower door test data above shows the typical fluctuation in the adjacent floor pressures as the test floor pressure is measured over a series of pressures. The data shown above and graphically displayed in Figure 4.3 was calculated using known a known air flow coefficient and exponent and is representative of resulting test data from the techniques described in this paper.

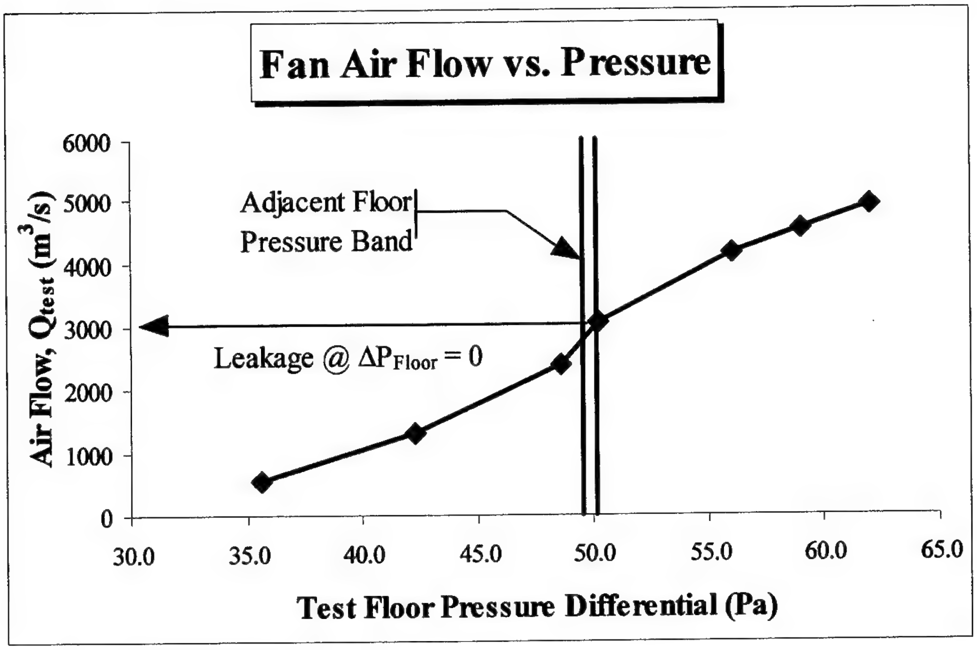


Figure 4.3 - Sample Envelope Leakage Graphical Analysis

The sample test data listed in Table 4.1 and plotted in the above Figure show the results for only one leakage test. In a given test period many of these data charts will be established for a range of pressures on the adjacent floors.

The zero inter-zonal leakage flow rate and corresponding pressure differential provides a single data point. The zero inter-zonal leakage air flow rates and pressure differentials derived from several groups of tests are used to determine the coefficients of Equation 4.2 by regression.

4.3 The Air Handler Method

The air handler method uses air handler fans to pressurize either a single building zone or the entire building. The test objective is to measure the envelope leakage associated with the test zone, which is equal to the quantity of outdoor air brought in by the system air handler that is required to maintain the interior pressure. The two major differences between this method and the floor-by-floor blower door method are the size of the zone served by the building air handler and the fan pressurization unit. In the air handler method, the test zone is defined as the part of the building served by the air handler to which the air flow is being measured. The test zone can be one of a series of air handler zones or a whole building, depending on the air handler configuration. The air handler fans are used to pressurize the test zone, replacing the need for blower doors.

The major advantage of the this method is the rapid installation of the flow measurement devices, all of which are centrally located within the air handler. Additionally, each of the air handler method testing procedures requires fewer total man-hours than the floor-by-floor blower door method to complete the testing. The main disadvantage of this testing method is that the location of the leaks in the exterior envelope cannot be determined as precisely as is possible with the floor-by-floor blower door method. However, if a building has more than one air handler, the zones in a building which provide larger leakage paths can be determined, since the air handler method reports the total leakage rate of a given air handling zone.

The following three methods can be used to quantify the outdoor air flow rate entering the air handler:

1. the tracer gas method;
2. the orifice plate method; and
3. the duct pitot traverse.

The tracer gas method is easily set up in the air handler. Good injection gas dispersion is needed. Enhanced mixing in the duct will improve the accuracy of the leakage test results. The orifice plate method measures the outdoor air flow base on a pressure differential measurement across an orifice of known area placed directly in the outdoor air path. The orifice plate must be calibrated on site because building features may alter the performance of the plate. The plate calibration may be difficult to complete with a pitot traverse or velocity grid if the air flow entering the plate is not parallel to the axis of the plate. Access to the outdoor air supply duct or grille is also required and often prevents the use of this technique in many high-rise buildings. A duct traverse is the most common method of measuring air flow rates. Flow must be relatively parallel to obtain accurate results (AMCA 1976).

The air handler fan is the pressurization source for each of the methods described above. To complete a series of air leakage tests, the test zone must be subjected to pressure differentials ranging from 12.5 to 75 Pascals (adopted from ASTM E779). To accomplish this, assuming 100 percent outdoor air, the fan air flow the must be reduced by adjusting the:

1. inlet or outlet vanes;
2. variable speed fan; or
3. OA damper position.

If the above methods cannot be used to obtain the desired pressure in the zone, the pressure differential can be further decreased by regulating the return air flow with the return air damper. The recirculated air flow will lower the zone pressure differential, but it will increase the uncertainty in the measured envelope leakage as it requires additional flow measurements.

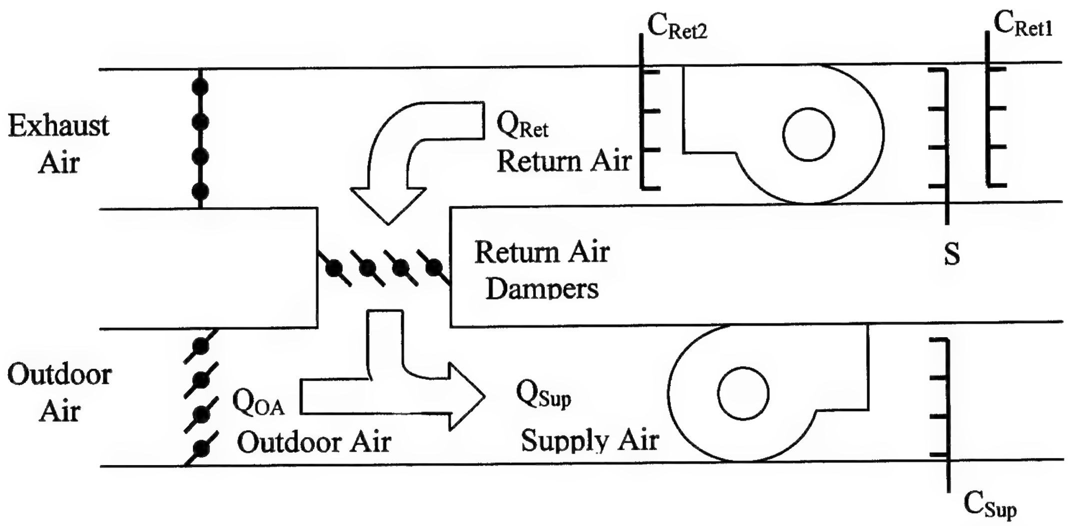
4.3.1 The Air Handler Method with Tracer Gas Flow Measuring Technique

4.3.1.1 Recirculating Air Flow

In the tracer gas method with recirculating air flow, a tracer gas is injected directly into the return air stream. The tracer gas must be injected evenly across the cross section of the duct to promote good mixing. A grid type injection/withdrawal mechanism designed to achieve this objective is described in detail in the Appendix A-2.1. Return air flow rate is determined from the measurement of tracer gas concentration upstream and downstream of the injection point and the rate of injection. The reduction of the tracer gas concentration from the return to the supply air stream is a function of the proportion of outdoor air mixed with return air. Therefore, three concentration measurements and one tracer gas flow measurement are needed to determine the outdoor air flow rate as shown in Figure 4.4. The system is set up quite easily.

Pressure must be measured on each floor throughout the test zone and on the two neighboring floors while the test is running to provide an accurate pressure estimate. The

pressure measurements must be examined to be sure that there is a normal seasonal pressure gradient within the building. After the measurements are verified, the pressure



differentials are then used to determine the overall leakage characteristics of the building.

<u>Figure 4.4 – Air Handler OA Flow Rate Measurement - Tracer Gas with Return Air</u>
Tracer Gas Method with Recirculating Air requires three Concentration Sensors, C_x, and one Supply Injection Grid, S.

Testing Procedure

The testing procedure for the air handler method with tracer gas flow measurement technique, using recirculating air flow is described in full detail in Appendix A-2.1. A summary of the test procedure is as follows:

1. Seal all interior air leakage paths to other air handling zones, including elevator shafts and exhaust grilles.
2. Seal the exhaust air damper.
3. Open all interior doors on the test zone and the two adjacent floors (excluding stairwell doors) to increase the uniformity of pressure across the floors.
4. Install the tracer gas injection grid (S) and withdrawal sampling grids (C_{Ret1}, C_{Ret2}, C_{Sup}) into the air handler, as depicted in Figure 4.4.

5. Lay out equally spaced pressure taps across each exterior face of the building for each floor in the test zone and the two neighboring floors. Each pressure tap should be installed at the mid-height of the floor being tested.
6. Adjust the air handlers to maintain the desired pressure differential across the test zone envelope, 12.5 to 75 Pascals.
7. Zero the pressure differential across the floor and ceiling of the test zone to minimize inter-zonal leakage. Adjust the air handlers to maintain the desired pressure in the adjacent zones. If the air handling fans can not achieve the desired pressure in the adjacent zones, the test floor pressure must be lowered until this requirement is satisfied.
8. Measure the pressure differential across each face of the building on every floor in the test zone and across the floors both directly above and below the test zone. The pressure measurements must be repeated over a three-minute time period to average out the effects of large pressure fluctuations due to wind gusts.
9. Run the pressure differential on the test zone through a series of values and measure the flow rate at each pressure. Each time the test zone pressure differential is changed, the pressure differentials on adjacent zones must also be changed to match. To avoid including excessive uncertainty in the results the target test pressure differentials should be 12.5, 25, 37.5, 50, 62.5, and 75 Pascals, following the guidelines established by ASTM Standard E779 (ASTM 1992).

A complete analysis of the building envelope leakage rate requires the combination of the test results over a range of floors as described in the following section.

Leakage Rate Analysis

Using the tracer gas concentration and injection rate measurements taken at the positions shown in Figure 4.4, the outdoor air flow rate at the air handler can be determined by means of tracer gas and air flow mass balances. The mass balances are completed at the injection point and mixed air section of the air handler.

$$Q_{\text{Ret}} = \frac{S}{(C_{Ret2} - C_{Ret1})} \tag{4.4}$$

(tracer balance at injection point)

$$Q_{Sup} = Q_{Ret}\left(\frac{C_{Ret2}}{C_{Sup}}\right) \tag{4.5}$$

(tracer balance at mixed air section)

$$Q_{OA} = Q_{Sup} - Q_{Ret} \tag{4.6}$$

(total air flow balance at mixed air section)

where,

Q_{Ret} = Return air flow rate (m^3/s)

Q_{Sup} = Supply air flow rate (m^3/s)

Q_{OA} = Outdoor air flow rate (m^3/s)

S = Tracer gas supply quantity (ppm * m^3/s)

C_{Ret1} = Tracer gas concentration in return air/building (ppm)

C_{Ret2} = Tracer gas concentration in return air after tracer gas injection (ppm)

C_{Sup} = Tracer gas concentration in supply air (ppm)

The simultaneous solution of these equations yields the outdoor air flow rate. The envelope leakage characteristics, C and n values, can now be calculated with a regression

analysis on Equation 3.2 using the measured pressure differentials and the outdoor air flow rates.

4.3.1.2 100% Outdoor Air

The tracer gas method with 100% outdoor air flow is very similar to the method previously described with the exception that the return air damper is sealed, thus prohibiting any return air from influencing the concentration measurements. Sealing the return air damper will simplify the data collection and will also reduce the chance for error by eliminating two concentration sensors. With both the return and exhaust dampers sealed, the air handler provides 100 percent outdoor air. Since 100 percent outdoor air is entering the system, only one tracer gas concentration measurement is needed downstream of the injection point.

The tracer gas is injected directly into the outdoor air upstream of the outdoor air dampers, or if not, as close to the outdoor air damper as possible, and the concentration is measured downstream of the fan, as shown in Figure 4.5. Because the flow rate through the fan will remain relatively constant, the measured tracer gas concentration will quickly reach steady state. In the previous method, the recirculating air tracer gas concentration gradually increased until the building reached a steady state concentration. This steady state concentration could take hours to achieve, but in the 100% outdoor air procedure the steady state concentration is achieved quickly since the recirculating air was eliminated. A summary of the testing procedure is provided in the following section.

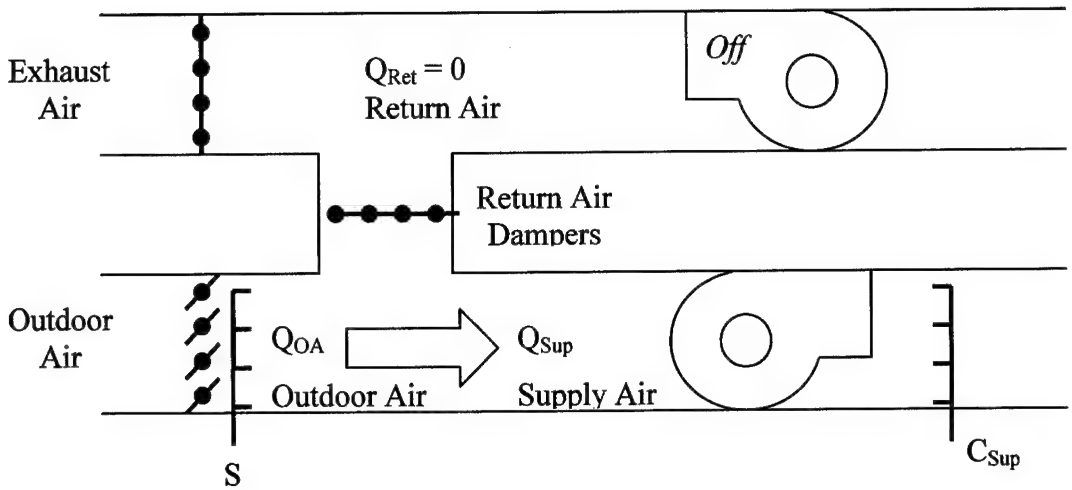


Figure 4.5 – Air Handler OA Flow Rate Measurement - Tracer Gas with 100% OA

The Tracer Gas Method with 100% Outdoor Air requires only 1 Concentration Sensor, C_{Sup}, and 1 Supply Injection Grid, S.

Testing Procedure

This section provides a summary to the testing procedure for the tracer gas flow measurement technique, with 100% OA. This procedure is described in full detail in Appendix A-3. In this procedure, as in the recirculating flow method, the test zone is defined as the air handler zone to which the air flow is being measured. The test zone can refer to one of a series of air handler zones or to a whole building, depending on the air handler configuration.

The test procedure is as follows:

1. Seal all interior air leakage paths to other air handling zones, including elevator shafts and exhaust grilles.
2. Seal the exhaust and return air dampers.
3. Open all interior doors on the test zone and the two adjacent floors (excluding stairwell doors) to increase the uniformity of pressure across the floors.

4. Install the tracer gas injection grid (S) and withdrawal sampling grids (C_{Sup}) into the air handler, as depicted in Figure 4.5.
5. Lay out equally spaced pressure taps across each exterior face of the building for each floor in the test zone and the two neighboring floors. Each pressure tap should be installed at the mid-height of the floor being tested.
6. Adjust the air handlers to maintain the desired pressures in the test zone, 12.5 to 75 Pascals.
7. Zero the pressure differential across the floor and ceiling of the test zone to minimize inter-zonal leakage. Adjust the air handlers to maintain the desired pressure in the adjacent zones. If the air handling fans can not achieve the desired pressure in the adjacent zones, the test floor pressure must be lowered until this requirement is satisfied.
8. Measure the pressure differential across each face of the building on every floor in the test zone and across the floors both directly above and below the test zone. The pressure measurements must be repeated over a three-minute time period to average out the effects of large pressure fluctuations due to wind gusts.
9. Run the pressure differential on the test zone through a series of values and measure the flow rate at each pressure. Each time the test zone pressure differential is changed, the pressure differentials on adjacent zones must also be changed to match. To avoid including excessive uncertainty in the results the target test pressure differentials should be 12.5, 25, 37.5, 50, 62.5, and 75 Pascals, following the guidelines established by ASTM Standard E779 (ASTM 1992).

A complete analysis of the building envelope leakage rate requires the combination of the test results over a range of floors as described in the following section.

Leakage Rate Analysis

Using the tracer gas concentration and injection rate measurements taken at the points shown in Figure 4.5, the outdoor air flow rate at the air handler can be determined by means of a single tracer gas mass balance:

$$Q_{OA} = \frac{S}{C_{Sup}} \tag{4.7}$$

where,

Q_{Sup} = Supply air flow rate (m^3/s)

Q_{OA} = Outdoor air flow rate (m^3/s)

S = Tracer gas supply quantity (ppm * m^3/s)

C_{Sup} = Tracer gas concentration in supply air (ppm)

The envelope leakage characteristics, C and n, can then be calculated for each test with the measured pressure differential and the outdoor air flow rate data through a regression analysis using Equation 3.2.

4.3.2 The Air Handler Method with Orifice Plate Flow Measuring Technique

The orifice plate method measures the outdoor air flow rate entering the air handler through a plate of known size and flow characteristics. The air handler is set up as in to the previous pressurization techniques, except that an airtight barrier, such as the combination of plywood and polyethylene sheet, is used to seal the outdoor air intake.

An orifice plate is constructed by cutting a circular hole, of known diameter, into the plywood to provide a flow path for the entering outdoor air, shown in Figure 4.6.

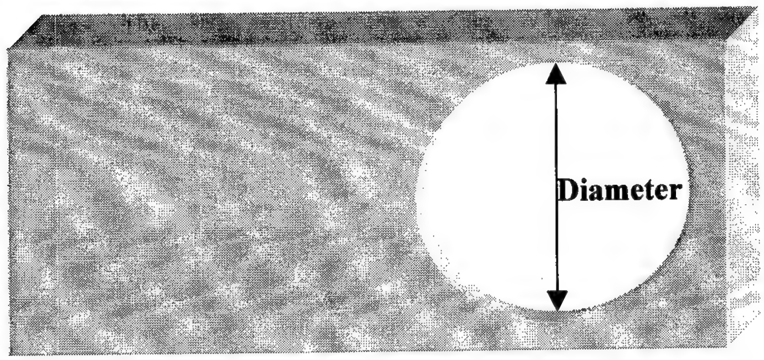


Figure 4.6 - Orifice Plate Design
The orifice plate was designed to extend as far away from the building wall as possible, yet still cover the outdoor air intake grille.

The outdoor air flow entering through the orifice plate must be uniform and undisturbed to use the standard orifice plate discharge coefficient of 0.61. Architectural or landscaping features of the testing site may prevent this, in which case the orifice must be calibrated in place. The orifice plate is calibrated in place using a pitot-static tube, tracer gas technique, or other velocity measuring method. The calibration establishes a correlation between the outdoor air flow rate entering the air handler and the pressure drop across the face of the orifice plate. Measuring both the velocity of the air traveling through the hole and the pressure drop across the plate, the total outdoor air flow rate can be determined. Using the measured outdoor air flow rate, the orifice plate is calibrated by solving for the flow characteristics of the orifice. Once the orifice plate has been calibrated, it is necessary to measure only the pressure difference across the plate to determine the flow rate.

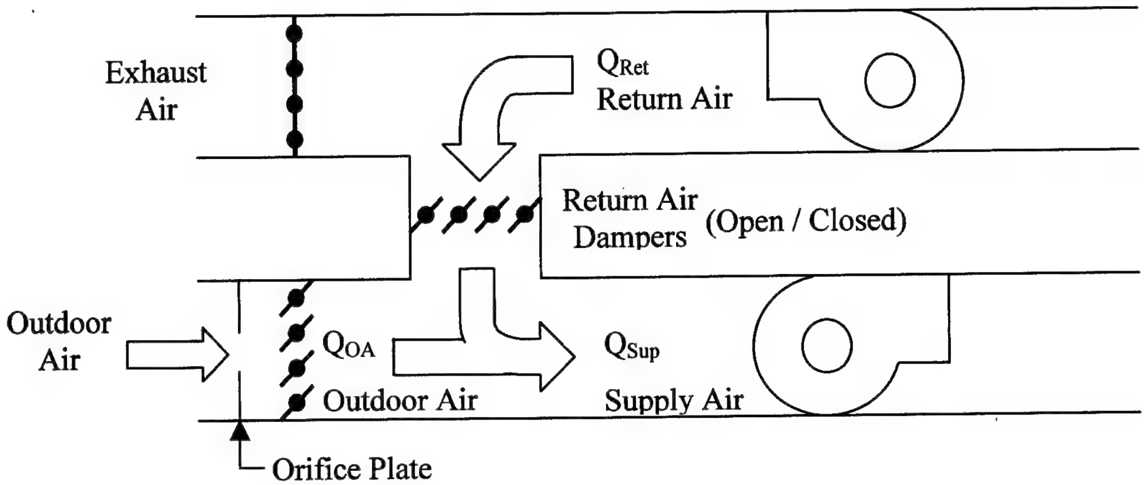


Figure 4.7 – Orifice Plate Method Schematic

This figure shows the orifice plate with the recirculating air flow arrangements, but the orifice plate set up is identical for 100% OA.

4.3.2.1 Testing Procedure

The air handler method with orifice plate flow measuring technique is described in full detail in Appendix A-3. A summary of the test procedure is as follows:

1. Seal all interior air leakage paths to other air handling zones, including elevator shafts and exhaust grilles.
2. Seal the exhaust (and return) air damper.
3. Install the orifice plate and vinyl sheet over the outdoor air grille of the test zone air handler only.
4. Open all interior doors on the test zone and the two adjacent floors (excluding stairwell doors) to increase the uniformity of pressure across the floors.
5. Lay out equally spaced pressure taps across each exterior face of the building for each floor in the test zone and the two neighboring floors. Each pressure tap should be installed at the mid-height of the floor being tested.

6. Adjust the air handlers to maintain the desired pressures in the test zone, 12.5 to 75 Pascals.
7. Zero the pressure differential across the floor and ceiling of the test zone to minimize inter-zonal leakage. Adjust the air handlers to maintain the desired pressure in the adjacent zones. If the air handling fans can not achieve the desired pressure in the adjacent zones, the test floor pressure must be lowered until this requirement is satisfied.
8. Measure the pressure differential across each face of the building on every floor in the test zone and across the floors both directly above and below the test zone. The pressure measurements must be repeated over a three-minute time period to average out the effects of large pressure fluctuations due to wind gusts.
9. Run the pressure differential on the test zone through a series of values and measure the flow rate at each pressure. Each time the test zone pressure differential is changed, the pressure differentials on adjacent zones must also be changed to match. To avoid including excessive uncertainty in the results the target test pressure differentials should be 12.5, 25, 37.5, 50, 62.5, and 75 Pascals, following the guidelines established by ASTM Standard E779 (ASTM 1992).

A complete analysis of the building envelope leakage rate requires the combination of the test results over a range of floors as described in the following section.

4.3.2.2 Flow Rate Analysis

The resulting data from an orifice flow measurement test will be a pressure differential across the orifice plate and an interior pressure differential. The relationship between the

pressure differential across the plate and the velocity is known to have the following characteristics:

$$C_D = \sqrt{\frac{V^2}{2g_c * \Delta P / \rho}} \tag{4.8}$$

where,

C_D = Discharge coefficient (constant, dimensionless)

V = Velocity through the plate (m/s)

g_c = 1.0 (kg-m)/(N-s^2)

ΔP = Pressure across the plate (Pa)

ρ = Air density (kg/m^3)

Once the discharge coefficient for the orifice plate is known, the flow rate through the plate can be calculated with the following equation (ASHRAE 1997).

$$Q = C_D A \sqrt{\frac{2\Delta P}{\rho}} \tag{4.9}$$

where,

Q = Flow rate (m^3/s)

A = Area of the plate (m^2)

Tests completed using orifice plates have shown that the discharge coefficient, C, should closely match the established value of 0.61. Knowing the flow entering the air handler and the interior pressure, the envelope flow coefficient and exponent can be solved for by performing a regression analysis as described in the Section 3.

4.3.3 The Air Handler Method with Pitot Traverse Flow Measuring Technique

The duct traverse method is commonly used by air balancing contractors to determine the air flow through a given section of ductwork. The outdoor air flow rate can be measured by two different techniques using the duct traverse method. The first technique is a single velocity traverse of the outdoor air intake. Unfortunately, it is often very difficult to get a good velocity profile from the outdoor air intake because of the system configuration. The second duct traverse method is to measure the flow rates in both the return and supply ducts. The additional pitot traverse required by this method will introduce additional uncertainty in the outdoor air flow rate calculation. The outdoor air flow is the difference between the supply and return flow rates, i.e.,

$$Q_{OA} = Q_{Sup} - Q_{Ret} \tag{4.9}$$

where,

Q_{OA} = Outdoor air flow rate (m^3/s)

Q_{Sup} = Supply air flow rate (m^3/s)

Q_{Ret} = Return air flow rate (m^3/s)

The air handler must be set up as in Figure 4.5 or 4.6, depending upon which configuration is chosen, (recirculating or 100% Outdoor Air). As the test is being conducted, it is important to record the pressure differentials across each face of the building on every floor in the test zone. The building air handler fans must be adjusted to develop a series of envelope pressure differentials ranging from 12.5 to 75 Pascals, specified by ASTM Standard E779 (ASTM 1992).

In general, the pitot tube traverse flow measuring technique is more cumbersome than the tracer gas and orifice plate methods previously described. It also requires skillful labor. Air balancing contractors, who commonly perform these air flow measurements, are most often employed during building commissioning. Performing a building envelope test during building commissioning would reduce the cost of the testing procedure, since the supply and return air flows must be measured during air balancing. Thus the required measurement equipment would already be set up, and the testing personnel would be on site. Additionally, there would be no tenants in the spaces, which would permit quick access to building floors.

4.3.3.1 Testing Procedure

The air handler method with pitot traverse flow measuring technique is described in full detail in Appendix A-4.

A summary of the procedure follows:

1. Seal all interior air leakage paths to other air handling zones, including elevator shafts and exhaust grilles.
2. Seal the exhaust and return air dampers.
3. Lay out equally spaced pressure taps across each exterior face of the building for each floor in the test zone and the two neighboring floors. Each pressure tap should be installed at the mid-height of the floor being tested.
4. Open all interior doors on the test zone and the two adjacent floors (excluding stairwell doors) to increase the uniformity of pressure across the floors.
5. Adjust the air handlers to maintain the desired pressures in the test zone, 12.5 to 75 Pascals.

6. Zero the pressure differential across the floor and ceiling of the test zone to minimize inter-zonal leakage. Adjust the air handlers to maintain the desired pressure in the adjacent zones. If the air handling fans can not achieve the desired pressure in the adjacent zones, the test floor pressure must be lowered until this requirement is satisfied.
7. Perform a velocity traverse downstream of the supply fan before any duct branches.
8. Measure the pressure differential across each face of the building on every floor in the test zone and across the floors both directly above and below the test zone. The pressure measurements must be repeated over a three-minute time period to average out the effects of large pressure fluctuations due to wind gusts.
9. Run the pressure differential on the test zone through a series of values and measure the flow rate at each pressure. Each time the test zone pressure differential is changed, the pressure differentials on adjacent zones must also be changed to match. To avoid including excessive uncertainty in the results the target test pressure differentials should be 12.5, 25, 37.5, 50, 62.5, and 75 Pascals, following the guidelines established by ASTM Standard E779 (ASTM 1992).

The measured flow rates and pressure differentials are then used to calculate the leakage characteristics of the building envelope using Equation 3.2.

5. Test Sites

The test sites in this research project were selected based on their size, differing mechanical system layouts, and owners' approval. The first building selected was the Pattee East Library, located at the Pennsylvania State University - University Park campus. Due to its availability and location on the campus, numerous leakage tests were performed at the Pattee East Library. This proved to be a valuable asset as the test methods could be refined during the day and tested in the evening hours. The second building that was selected for envelope testing was the USX Building in Pittsburgh, Pennsylvania. A brief description of each building is presented below.

5.1 Pattee East Library (University Park, PA)

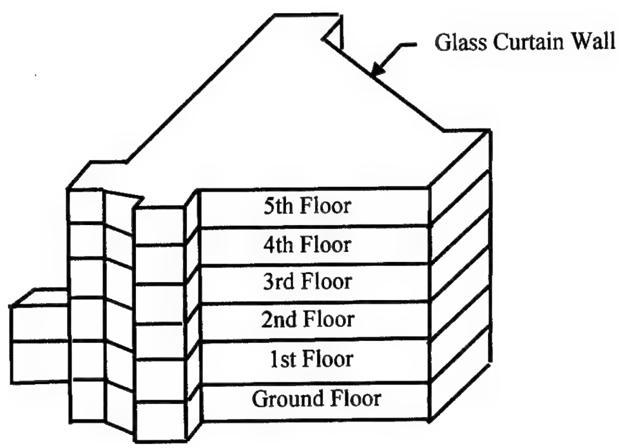


Figure 5.1 - Pattee East Library

The Pattee East Library is a 12075 m^2 (130,000 ft^2) extension to the main library at the Pennsylvania State University. It is characterized both by its nearly triangular footprint and also a glass curtain wall on the northeast face of the building that extends from the ground level to the top of the building. This building is six stories in height with two internal elevator shafts and three perimeter stair shafts. The two elevator shafts and the main stairwell each have exterior doors located on the roof. The three stairwells also

have fire doors located at ground level. Each of the first 5 levels has an open floor plan with offices and study rooms located to the south and west faces of each floor. The fifth floor is an open office and is divided into cubicles. The fifth floor is the only floor outfitted with operable windows.

The Pattee East Library has a central air handling system located in the mechanical room on the ground level. This air handling system supplies floors one through four. Two external air handling units located on the roof are used to condition the air on the fifth floor. The central air handling system on the ground floor has two main supply air fans which supply 36.8 m^3/s (78,000 cfm) and 31.6 m^3/s (67,000 cfm) respectively. There are also two return fans with capacities of 43.9 m^3/s (93,000 cfm) and 20.8 m^3/s (44,000 cfm). The lavatories are served by an exhaust fan located on the roof.

5.2 USX Tower, (Pittsburgh, PA)

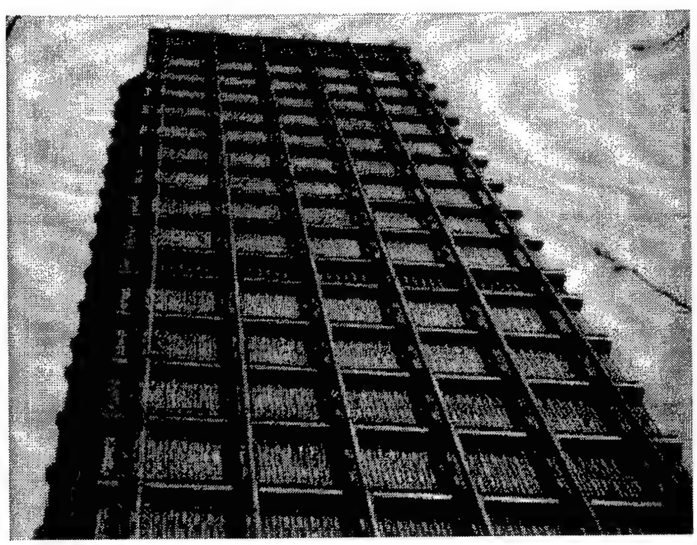


Figure 5.2 - USX Tower

The USX Tower is a 256 meter (841 ft) tall office building located on Grant Street in downtown Pittsburgh, Pennsylvania. The tower was built by the US Steel corporation in

the late 1960's and still stands as Pittsburgh's tallest structure. The 64 story building encloses approximately 270,000 m^2 (2.9 million ft^2) of floor area, of which 220000 m^2 (2.4 million ft^2) is leasable. The building is supported by an external steel frame. The horizontal support members seen in Figure 5.2 are spaced every three floors. All windows in the building are operable and are opened only for cleaning purposes.

There are four mechanical rooms located throughout the USX Tower (on floors 3, 34, 63-64, and the general concourse level). Both the 34th and 63rd floor mechanical rooms are characterized by vertical louvers, and can be seen in Figure 5.2. The building is served by one central cooling plant, located on the 63rd floor mechanical room.

Air leakage testing in the USX Tower was performed only in the upper zone which spans floors 49 through 61. Supply fans are designed to transport a total of 236 m^3/s (500,000 cfm) to this zone from air handlers located on the 64th floor. Approximately 189 m^3/s (400,000 cfm) is returned from those floors. To achieve the desired pressures required for the air handler test procedure, only two supply air handlers, each with a capacity of 45.3 m^3/s (96,000 cfm), were used.

6. Test Equipment

The equipment used in the envelope leakage tests described in this report include:

1. Blower doors
2. Digital pressure gauges
3. Orifice plate
4. Pitot tubes and velocity grid
5. Tracer gas monitor (gas chromatograph)

The ***blower door*** fan is constructed of molded plastic and contains a .56 kW (3/4 hp) AC motor with a design flow of 3.0 m^3/s (6,400 cfm). The unit, calibrated by the manufacturer, also came with two factory calibrated flow restricting rings that are capable of measuring flows as low as 0.14 m^3/s (300 cfm), without losing any accuracy. The fan flow measurements have been shown to be accurate to within ±3 percent of the actual flow. The blower door and door frame kit was accompanied with software that allows a laptop computer to automatically record the blower door results. The software also permits the user to digitally control the fan by setting differential pressure to be maintained in the space.

Three ***digital pressure gauges*** were used to measure the pressure differential across each face of the building during the pressurization testing. Each pressure gauge was self calibrating and equally accurate. These instruments are designed to read pressures from 0 to 199.9 Pa with an accuracy of ±1 percent of the pressure reading.

Two ***orifice plates*** were constructed on site at the Pattee East Library, each with an 2.4 m x 1.2 m (8 ft x 4 ft) sheet of plywood. A single 1.07 m (3.5 ft) diameter circle was

inscribed and cut into each plywood sheet. The plywood was then attached around the perimeter to 5.1 cm x 15.2 cm (2 in x 6 in) board on end (as depicted below in Figure 4.6). The boards were used to raise the orifice plate up off the outdoor air grille. The two orifice plates were spaced twelve feet apart and the remaining area of outdoor air grille was covered with a non-permeable plastic sheet.

The ***pitot-tube*** and ***velocity grid*** were used both to measure and to calibrate the flow through the orifice plate. The pitot-tube is designed to measure a range from 25 to 10,000 fpm with an accuracy of ±3 percent of the reading. The velocity grid provides the average velocity through a 35.6 cm x 35.6 cm (14 in. x 14 in.) square, represented by 16 pressure measurement points. The velocity grid is capable of measuring a range from 0.012 m^3/s (25 cfm) to 1.18 m^3/s (2500 cfm) with an accuracy of ±3 percent of the reading.

The automatic ***tracer gas monitor*** used was a microprocessor controlled electron capture gas chromatograph. The monitor was used to measure the concentration of sulfur hexafluoride present in the space. The tracer gas device is outfitted with an onboard calibration gas diluted in ultra-pure air. This unit also has an onboard vacuum pump that is used to pull the test air into the chromatograph. This pump is able to purge 91.4 meters (300 feet) of 0.32 cm (1/8 in) polyethylene tubing before injecting the gas sample to be analyzed. The measurements are digitally stored on a disk during the testing and later retrieved for test analysis. The accuracy of the tracer gas monitor is ±3 percent of the reading in the linear dynamic range, 0.05 to 10 ppb.

7. Envelope Leakage Tests

7.1 Introduction

The testing procedures described in Chapter 4 provide a variety of techniques to measure the envelope leakage rate in tall buildings. Both the floor-by-floor blower door method and the air handler method were tested in Pattee East Library. Several flow measurement techniques were tested at the Pattee East Library, including blower doors, the tracer gas techniques, and the orifice plate technique. Time restrictions and availability of the USX Tower limited testing to a single envelope leakage test method. Of all the methods tested at the Pattee East Library, the air handler method with 100% outdoor air was the most suitable for testing at the USX Tower. The following sections describe the results that we obtained from each method tested at both buildings.

7.2 Floor-by-Floor Blower Door Test Results

Many attempts were made to validate the floor-by-floor blower door testing method at the Pattee East Library. The results consistently demonstrated that isolating a single floor in a large building is nearly impossible. The elevators, doors, ducts, and other obvious leakage paths were all completely sealed, yet there existed a tremendous amount of additional, inaccessible floor-to-floor leakage. This was proven by the fact that with the test floor sealed and the adjacent floors pressurized, high pressures were recorded on the testing floor when the blower door fan was off. After further efforts to find and seal every leakage path, the same erroneous results were obtained. During the search for leakage paths, numerous holes and cracks in the return risers and elevator shafts were found that were physically impossible to reach and seal. Additionally, the return air shaft was found to be constructed of 16 inch concrete masonry unit (CMU) blocks that have

only a small resistance to air flow. These CMU blocks constitute yet another inter-floor leakage path within the building. Sealing the return shaft in the Pattee East Library was an impossible task. Therefore it was not possible to successfully apply the floor-by-floor blower door test method.

In buildings with floor-by-floor air handling systems, this type of testing method may be used more successfully. In these buildings, there are no supply or return risers that generally act as large leakage paths. However, there are still elevator and stair shafts that must be sealed. In the Pattee East Library the elevator shafts were constructed of poured concrete and were almost completely resistant to leakage once the doors were sealed with a plastic sheeting. If it is determined that these vertical shafts will not enhance inter-floor air leakage then this method would be ideal for buildings with floor-by-floor air handlers. The air handlers on each floor must be manipulated, as shown in Figure 4.2, to maintain the pressure on the adjacent floors. The testing floor must be sealed, including the air handler, and the blower door (s) can be used to pressurize the testing floor. Analysis can be completed as previously discussed. It is also possible to use the air handler on each floor to pressurize the space, essentially conducting the air handler method, as described in Section 4.3.

7.3 Air Handler Method with Tracer Gas Results

The leakage rates of Pattee East and the USX Tower were tested using the tracer gas flow measurement technique. In both buildings the envelope leakage was tested using the tracer gas with the 100% outdoor air method, as described in Section 4.3.1.2. The return air damper was closed and sealed with plastic sheeting to prevent any recirculating air

from entering the supply fan. Sulfur hexafluoride was injected across a grid at the outdoor air dampers, and the concentration was measured downstream of the supply fan.

Using this method the results obtained were consistent and repeatable. The concentration over two typical, 12-minute tests at Pattee East Library on 9 July 1997 is shown in Figure 7.1. The associated outdoor air flow rates were calculated using Equation 4.7. This graph indicates how similar the tests actually were and how rapidly a steady state was approached. A complete set of graphs detailing each of the completed tests is included in Appendix B. The actual outdoor air flow rates used to compute the envelope leakage flow coefficient and exponent were the average of the last three measured values for each test run, (minutes 8, 10, and 12). These three values were selected because, as it can be seen from the graph, the tracer gas concentration had reached a steady state.

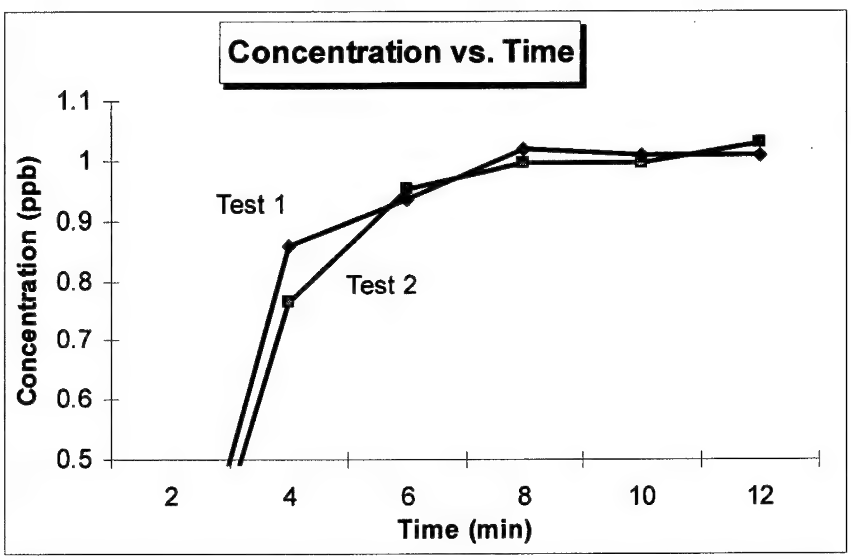


Figure 7.1 - Pattee East Library Test Data (9July 1997)
The Pattee East Library Test Data from 9 July 1997 shown in the above figure shows two tests completed with the same operating conditions. This example shows how quickly the concentration reaches steady state and the excellent repeatability of the tests. The flow rate was solved as a function of the concentration using Equation 4.7.

Table 7.1 displays the results of eight tests completed at the Pattee East Library on 9 July 1997. The results include the test number, differential pressure, and the corresponding air flow. Because the pressure differentials are not linearly related to the flow rates, they cannot be averaged linearly. For each test a representative differential pressure was determined using non-linear area weighted averaging as shown in Equation 7.1.

$$\Delta P_{Avg} = \left(\frac{\Delta P_1^n \cdot A_1 + \Delta P_2^n \cdot A_2 + \ldots + \Delta P_x^n \cdot A_x}{A_{Total}} \right)^{\frac{1}{n}} \tag{7.1}$$

where,

ΔP_{Avg} = Average Pressure Differential (Pa)

ΔP_x = Pressure Differential across the Exterior Wall on the X'th Floor (Pa)

n = Flow Exponent

A_{Total} = Total Exterior Wall Area (m^2)

A_x = Exterior Wall Area corresponding to the recorded pressure differential (m^2)

Pattee East Library 9 July 1998		
Test No.	ΔP (Pa)	Q (cfm)
1	12.2	63778
2	12.5	58751
3	9.6	52912
4	9.64	52586
5	7.18	44926
6	6.9	42070
7	4.98	38912
8	3.98	38615

Table 7.1 - Pattee East Library Test Results (9 July 1997)

The pressure differentials shown in Table 7.1 are below the recommended target pressure differential range of 12.5 to 75 Pascals. The maximum zone pressure differential was limited to 12.5 Pascals due to the excessive leakage caused by ongoing construction at the Pattee East Library

Assuming constant flow coefficients and exponents over the entire air handler zone, the C and n values were solved for using the representative floor pressures and the outdoor air flow rates. An equation solving software package (EES 1997) was programmed to perform the regression analysis previously described in Section 3. The program is described in more detail in Appendix C. The program identifies the flow coefficient and exponent that minimize the root mean square error between the experimental flow results obtained on site and the model-generated results as described by Equation 4.3. Equation 3.2 was used to solve for the average C and n values, allowing each floor pressure, from Equation 7.1, to be individually input as shown below in Equation 7.2, (equation 3.2 expanded). The wall areas for each of the five floors in the Pattee East Library were equal, therefore the areas cancelled out of Equation 3.2 in this analysis.

$$Q_{OA} = C\frac{\sum_{i=1}^{M} A_i \Delta P_i^n}{A_{Total}} = C\frac{\left(A_S \cdot \Delta P_1^n + A_S \cdot \Delta P_2^n + A_S \cdot \Delta P_3^n + A_S \cdot \Delta P_4^n + A_S \cdot \Delta P_5^n\right)}{5A_S} \tag{7.2}$$

where,

Q_{OA} = Outdoor Air Flow Rate (m^3/s)

P_x = Pressure Drop across the Exterior Wall on the X'th Floor (Pa)

C = Flow Coefficient [$m^3/(s \cdot Pa^n)$]

n = Flow Exponent

Equation 7.2 was used to determine the predicted flow rate for each test, combining all the floor pressures. Values of C and n were selected to minimize the square error for all test data, using Equation 4.3. The flow coefficients calculated in Equation 7.2 are on a "per floor" basis. As indicated in Section 3, only a representative flow coefficient and

exponent were calculated for each building. Determining the flow coefficient on a "per wall" basis is beyond the scope of this project.

In the USX Tower the upper zone consisted of a total of 13 floors, which would introduce an additional eight pressures into Equation 7.2. The pressurization tests were completed over a pressure range of 75 to 150 Pascals. Higher pressures were used in this building because at lower pressures, the pressure drop across the envelope was not equal due to the air system configuration. It should also be noted that the general leakage condition of the building envelope was poor as window seals were brittle and easily penetrated. A complete list of the differential pressures, air flow rates, flow coefficients, and flow exponents is displayed in Appendix D.

Tables 7.2 and 7.3, list the C, n, and Q_{50} values for both the Pattee East Library and the USX Tower.

Pattee East Library			
Date	*C* ($m^3/(s \cdot Pa^n)$)	*n* (dimensionless)	Q_{50} (m^3/s)
9 July 1997	1.62	0.46	9.79
10 July 1997	1.73	0.44	9.67
16 July 1997	1.81	0.42	9.36

Table 7.2 - Pattee East Library Results

Table 7.2 displays the results for the Air Handler Method with Tracer Gas Measuring technique with 100% outdoor air. The C and n values are the result of 8-10 pressurization tests on each test date. Q_{50} is a standard leakage measurement rate using the fitted values of C and n to determine flow rate at 50 Pascals.

USX Tower			
Date	*C* ($m^3/(s \cdot Pa^n)$)	*n* (dimensionless)	Q_{50} (m^3/s)
10 August 1997	0.19	1.30	30.72

Table 7.3 - USX Tower Results

Table 7.3 displays the results for the Air Handler Method with Tracer Gas Measuring technique with 100% outdoor air. The C and n values are the result of 10 pressurization tests completed. Q_{50} is a standard leakage measurement rate using the fitted values of C and n to determine flow rate at 50 Pascals.

7.4 The Air Handler Method with Orifice Plate Results

The orifice plate testing method was performed only at the Pattee East Library because the outdoor air duct and grille in the USX Tower were not accessible. At the Pattee East Library the outdoor air grille was at ground level and was very accessible. Two orifice plates were placed directly on the outdoor air grille. The orifices were fabricated by cutting three foot diameter holes into two plywood. Calibration of flow as a function of pressure differential was obtained by use of a velocity grid. The velocity grid provides the average velocity through a 35.6 cm x 35.6 cm (14 in x 14 in) square, represented by 16 pressure measurement points. A relationship between the pressure across the plate and the velocity was determined using Equation 4.8.

The discharge coefficient, C_D, was approximately 0.80 $m^3/(s \cdot Pa^n)$ on each plate. This value is substantially higher than the expected value of 0.6 $m^3/(s \cdot Pa^n)$. This could be caused by either inaccurate flow measurements or the effect of the building architecture on the flow entering the orifice plate (the OA grille was located perpendicular to the building wall). The results of the orifice plate tests are shown in Table 7.4. The variance of the C and n values in this table is the result of ongoing construction at the Pattee East Library. A new wing is being added to the building and the envelope leakage increased noticeably as construction proceeded.

The results presented here for orifice plate tests are much different than those published for the Pattee Library in the Tracer Gas section. This is due in large part to the early start of the construction schedule at the Pattee East Library, an event beyond the control of the

Pattee East Library			
Date	*C* ($m^3/(s{\cdot}Pa^n)$)	*n* (dimensionless)	Q_{50} (m^3/s)
21 May 1997	0.094	1.48	30.73
22 May 1997	0.066	1.56	29.51
28 May 1997	0.416	1.12	33.26
29 May 1997	0.750	0.96	32.07

Table 7.4 - Pattee East Library Results

Table 7.4 shows the results obtained from the Air Handler Method with Orifice Plate Measuring Technique. The C and n values are the result of 10 pressurization tests on each test date.

authors that made completion of required testing very difficult. The tracer gas tests were completed after the glass curtain wall was removed from the north-east side of the building while the orifice plate tests were done during its removal. Consequently the orifice plate results show an increasing leakage trend that specifically indicates that the building envelope was being altered and that the envelope airtightness was decreasing throughout the testing phase of the project.

8. Discussion

8.1 Application of Leakage Test Methods

The test procedures considered in this research can be used to measure envelope leakage in a variety of tall buildings. However, because of the variety of HVAC system types found in tall buildings, no single test procedure would be universally applicable to all tall buildings. The specific envelope leakage test procedure to be used in each application will be determined based on the properties of the building being tested. A major factor in the selection of the best test procedure is the building's air handling system design. Simply stated, a building designed with centralized air handling units includes numerous additional inter-floor leakage paths in the form of supply and return shafts. These flow paths hinder the ability to completely seal a single floor. Sealing the ductwork and shaft penetrations in a single floor test can prove to be a large, time consuming task. In this situation, the air-handling system method will provide the best results. On the other hand, a building designed with floor-by-floor blower door air handling units can be best tested using the floor-by-floor envelope leakage test method. Set up time will mainly consist of sealing the elevator and stair shafts, a much easier task then sealing the ductwork.

The floor-by-floor blower door test procedure uses a simple approach to determine the envelope air leakage rate. The largest drawback in this test method is the set up time. It took a group of four workers nearly three hours to seal a single floor in Pattee Library, including ductwork. This time would be drastically reduced if the supply and return ducts were eliminated. In large buildings with numerous elevator and stair shafts, the sealing process time will increase, but it can be completed during the day on unoccupied

floors. In fact, once a single floor has been tested, the materials from that floor can be saved and recycled on the next floor, reducing the set up time. A blower door test can be completed with either a one or two-man crew. The main tasks would be to reset the blower door to run at a series of pressures and to continually observe the floor, while making sure the seals remain in place.

The air handler method requires a working knowledge of either the tracer gas testing equipment or the flow measurement equipment is also a requirement. To avoid user error from influencing the results, it is recommended that the user become very familiar with the testing equipment before conducting an envelope leakage test.

Fortunately, the air handler method testing procedure is quickly set up in the mechanical room and testing can then begin immediately. Once the tester has gained the knowledge to run this test procedure, testing can be completed quickly and smoothly without interruptions. The tracer gas method was studied in great detail throughout this research project at the Pattee East Library and it was easily implemented into the USX Tower with the knowledge of the system layout that was gained from an inspection of the design drawings and one brief visit to the building. In fact, a complete air handler test was performed in under seven hours, including system set up and breakdown.

8.2 Fire Safety Considerations

A common procedural step in all the methods described throughout this report is to open all interior doors in the zone being tested. Propping fire doors open can create the risk of the spread of smoke or fire for both the testing personnel and the building occupants.

The responsibility of safety must be accepted by the testing agency and a plan of action in the unlikely chance of fire must be designed.

This plan should include the closure of all fire doors upon the notification of a fire within the building. This could be done manually if sufficient personnel are available to close the doors in a timely manner. It could also be carried out mechanically. For example, a device such as an electromagnet could be employed to hold each of the doors open. Assuming the electromagnets are all powered by a single circuit, and that they operate in a fail safe mode, when the power is turned off in a single location, all the doors will shut. Many modern buildings are provided with fire doors held normally open in this manner by electromagnets controlled by the fire alarm system.

Regardless of the method used to close the doors, a written fire protection contingency plan must be supplied to all test personnel, and they should be trained in it's implementation. Also, an instruction sheet should be distributed to all of the regular building occupants who will be in the building during the test. This sheet should explain the purpose of the test, any impact that it will have on the building conditions, and the action that will be taken in case of fire.

8.3 Error Analysis

A root mean square (rms) error analysis has been completed for the tracer gas outdoor air flow rate method to determine the measurement uncertainty of the procedure studied. This error analysis has been completed in accordance with the methods set forth by Doebelin (1983). This uncertainty is based upon the error in the individual components used during the test. The total system error is not the algebraic sum of the individual

component errors, which are essentially the absolute limits, but it is a function of these errors. The outdoor air flow rate can be computed by entering the test results, three concentrations and one tracer gas supply flow rate, into Equations 4.4,4.5, and 4.6. The form of the general equation including component and total error is described below.

$$Q_{OA} + \Delta Q_{OA} = f\,(C_{Ret1}+\Delta C_{Ret1}, C_{Ret2}+\Delta C_{Ret2}, Q_{Ret}+\Delta Q_{Ret}, S+\Delta S) \pm \text{Inter-Zone Leakage} \quad (8.1)$$

where,

Q_{OA} = Outdoor air flow rate (m^3/s)

ΔQ_{OA} = Error in the measured outdoor air flow rate (m^3/s)

S = Tracer gas supply quantity (ppm * m^3/s)

ΔS = Error in the measured tracer gas supply quantity (ppm * m^3/s)

C_{Ret1} = Tracer gas concentration in return air/building (ppm)

ΔC_{Ret1} = Error in the measured tracer gas concentration in return air/building (ppm)

C_{Ret2} = Tracer gas concentration in return air after tracer gas injection (ppm)

ΔC_{Ret2} = Error in the measured tracer gas concentration in return air after tracer gas injection (ppm)

C_{Sup} = Tracer gas concentration in supply air (ppm)

ΔC_{Sup} = Error in the measured tracer gas concentration in supply air (ppm)

The errors noted in Equation 8.1 are specified by the equipment manufacturer in the accompanying product literature. The SF_6 distribution error can be caused by a loss in the tracer gas in the supply fittings or by uneven tracer gas distribution throughout the duct section. This error is combined with the supply flow rate error, S, in Equation 8.1. In that equation, inter-zone leakage is the air that is lost from the testing zone to the adjacent building zones.

Using the Taylor series expansion the measured outdoor air flow rate and associated error can be generally described as follows:

$$Q_{OA} + \Delta Q_{OA} = f\,(C_{Ret1}+\Delta C_{Ret1},\ C_{Ret2}+ \Delta C_{Ret2},\ Q_{Ret}+ \Delta Q_{Ret},\ S +\Delta S) \pm \text{Inter-Zone Leakage} + \Delta C_{Ret1}(\partial f \,/\, \partial \Delta C_{Ret1}) + \Delta C_{Ret2}(\partial f \,/\, \partial \Delta C_{Ret2}) + \ldots \tag{8.2}$$

The higher order differentials are disregarded in this application because the individual errors are all quite small, making terms such as $(\Delta C_{Ret1})^2$ inconsequential. Using this simplification, the absolute error is given in the following equation.

$$\text{Error} = \Delta Q_{OA} = \left|\ \text{Inter-Zone Leakage}\right| + \left|\Delta C_{Ret1}(\partial f \,/\, \partial \Delta C_{Ret1})\right| + \left|\Delta C_{Ret2}(\partial f \,/\, \partial \Delta C_{Ret2})\right| + \left|\Delta Q_{Ret}(\partial f \,/\, \partial \Delta Q_{Ret})\right| + \left|\Delta S(\partial f \,/\, \partial \Delta S)\right| \tag{8.3}$$

Equation 8.3 describes the absolute bounds for error in the outdoor air flow rate. The relative error can be computed by dividing the total error from Equation 8.3 by the outdoor air flow rate. While this equation is useful in solving the limits of the error, the probability of this error is small. Therefore, the equation must be modified to compute the statistical bounds such as the probable error. The correct procedure to combine the errors noted above is to compute the root-sum square (RSS) value as shown in the following formula:

$$\text{Error}_{RSS} = [(\text{Inter-Zone Leakage})^2 + (\Delta C_{Ret1}(\partial f \,/\, \partial \Delta C_{Ret1}))^2 + (\Delta C_{Ret2}(\partial f \,/\, \partial \Delta C_{Ret2}))^2 + (\Delta Q_{Ret}(\partial f \,/\, \partial \Delta Q_{Ret}))^2 + (\Delta S(\partial f \,/\, \partial \Delta S))^2]^{0.5} \tag{8.4}$$

The RSS error calculated from Equation 8.4 will result in a lower error value than that calculated from Equation 8.3. This lower error value is statistically correct if the component error describes the $\pm 3\sigma$ limits. If this requirement holds true, then the calculated outdoor air flow rate will fall in this RSS error limit 99.7 percent of the time. The derivatives to the outdoor air flow rate equation are listed in provided in Appendix E.

Table 8.1 describes the input errors as either published by the equipment manufacturer or conservatively estimated using knowledge of the site.

Source of Error	Error (%)
1. SF_6 Concentration Supply Flow Rate Reading Error (ppb * L/s)	3
2. SF_6 Supply Flow Loss in Fittings (pps * L/s)	5
3. Uneven SF_6 Distribution in Duct (ppb * L/s)	10
4. Return 1 Concentration Reading Error (ppb)	3
5. Return 2 Concentration Reading Error (ppb)	3
6. Supply Concentration Reading Error (ppb)	3
7. Inter-Zone Leakage (L/s)	5

Table 8.1 - Component Error Values

The resulting outdoor air flow rate error was calculated using the these component error values coupled with three representative test results. The actual error was calculated for three tests for both tracer gas methods, with and without recirculating air flow, to determine a representative error band. Both the total error and representative error are presented.

	Tracer Gas with Recirculating Air		Tracer Gas with 100% Outdoor Air	
Test	**Total Error (30.7 m^3/s total {65,000 cfm})**	**Representative Error**	**Total Error (62.5 m^3/s total {132,500 cfm})**	**Representative Error**
1	3414 cfm	6.4 %	6782 cfm	5.6 %
2	3360 cfm	5.8 %	6728 cfm	5.4 %
3	3331 cfm	5.4 %	6743 cfm	5.4 %

Table 8.2 - Pattee East Library Results

Table 8.2 shows both the total and representative error in leakage flow rate found in the test results for the Pattee East Library. Three representative tests were analyzed in the study.

The error for the tracer gas with 100% outdoor air method was calculated using the same procedure that is described above. In this case, the outdoor air is now only a function of the tracer gas supply and one concentration reading. Because only one concentration measurement is required, error for the 100% outdoor air method is smaller than for the

method with recirculation. However, the error introduced by the two additional concentration readings required when there is recirculation was quite small, as shown by the differences in representative error in Table 8.2. This exercise showed that the flow rate measurement error in the tracer gas method is small, roughly 5-6 percent with 100% outdoor air, suggesting that this method is a viable approach to the measurement of the airtightness of small buildings.

Estimated Q_{50} Uncertainty

The objective of this analysis is to estimate the total uncertainty in the resulting leakage flow rate, Q_{50}. The error analysis procedure outlined thus far estimates the uncertainty in the flow rate measurement. The uncertainty range in the flow rate measurement was calculated to be 5.4 to 6.4 percent, from Table 8.2. Additional uncertainty from the pressure measurement must be included to determine the overall uncertainty in the resulting estimate of the leakage flow rate. Pressure measurement uncertainty is a result of the combination of the pressure sensor instrument uncertainty and the wind pressure error. The instrument error is one percent of the pressure reading, and was established by the pressure sensor manufacturer. The wind error is a function of the wind speed, number of pressure sensors, location of pressure sensors, and orientation of the building. This error has been analyzed in Section 3.2 and the results will be used to calculate the overall uncertainty in the leakage flow rate estimate.

The leakage rate estimate at 50 Pascals, Q_{50}, is the most common comparison of envelope leakage values (Sherman and Palmiter 1995). It is performed by using the flow coefficient and flow exponent, calculated by regression analysis on the test data, to

estimate the leakage rate at 50 Pascals. The uncertainty introduced by a poor fit to the test data must be accounted for in this procedure. Deriving the statistical uncertainty in the leakage flow rate estimate requires mathematics beyond the scope of this project. Therefore, a method was devised to estimate the total error by randomly weighting the errors in the flow rate and pressure values with a random number generator. The following steps were performed to complete this error analysis.

1. Calculate perfect data using Equation 3.1. For this analysis the authors arbitrarily chose the following constant values: $C = 10\ m^3/(s{\cdot}Pa^n)$ and $n = 0.6$;
2. Determine the error due to wind for one to six sensors per wall face at the highest recommended wind speed, 4 m/s, from Figures 3.2, 3.3, 3.4;
3. Determine the error in the flow rate measurement, Table 8.2;
4. Generate "data" including normally distributed random errors in the flow and pressure having standard deviations equal to the estimated RMS measurement uncertainties for flow and pressure. The pressure differential "measurements" were taken at nominal values of 12.5, 25, 37.5, 50, 62.5, and 75 Pa;
5. Perform a regression analysis on the flow rates and pressures with added random error.
6. Use the new flow coefficient, C', and flow exponent, n', to calculate the predicted flow rates at the pressure differentials listed above in step 3;
7. Calculate the root mean square (RMS) error at each as a percentage for each set of representative data: pressure differential "measurements" and predicted air flow rates.
8. Repeat steps 1 to 8 ten times for one to six sensors per wall face.

9. The average RMS error was determined from the ten runs for one to six sensors.

Table 8.3 displays the results of this analysis.

Number of Sensors per Wall Face	Total Error in the Flow Rate
1	3.28 %
2	3.43 %
3	3.21 %
4	3.16 %
5	3.23 %
6	2.96 %

Table 8.3 - Total Uncertainty in the Flow Rate Estimate (4 m/s)
Table 8.3 shows the total percent error in the flow rate estimate. The wind speed was a constant value of 4 m/s.

An analysis of this uncertainty measurement indicates that the number of pressure sensors across the face of the wall does not decrease the overall uncertainty in the flow measurement. This result may seem counterintuitive, however, it results from the fact that the flow measurement uncertainty is twice as large as the pressure measurement uncertainty at a wind speed of 4 m/s. If on the other hand it is not a result of the small error in the pressure measurement, it could be an indication that the random number generator has influenced the uncertainty estimates. To test this hypothesis, the uncertainty analysis was performed as described above, but at a wind speed of six m/s. Table 8.4 displays the results of this analysis.

An analysis of the uncertainties in Table 8.4 support the fact that the uncertainty in Table 8.3 is a function of the larger flow measurement uncertainty and not of the random numbers. In both the uncertainty analyses, the error is less than four percent. This indicates that the air handler method with 100% outdoor air flow measuring technique

will provide highly accurate results. The air handler method with recirculating air will produce slightly higher uncertainty as the error in flow measuring technique is approximately 1% higher.

Number of Sensors per Wall Face	Total Error in the Flow Rate
1	4.58 %
2	3.87 %
3	3.83 %
4	3.09 %
5	3.01 %
6	2.98 %

Table 8.4 - Total Uncertainty in the Flow Rate Estimate (6 m/s)

Table 8.4 shows the total percent error in the flow rate estimate. The wind speed was a constant value of 6 m/s.

9. Summary and Conclusions

There is currently no standard that focuses on the measurement of envelope leakage in tall buildings. This thesis has reviewed the current methods used to measure the envelope leakage rate and evaluated their applicability to tall buildings. The two current envelope leakage pressurization standards, ASTM Standard E779 (1992) and the CAN/CGSB-149.15 (1996), provide no guidelines for problems arising in tall buildings such as the magnitude of the stack and wind effects. However, the established methods provide a variety of options suitable for development into methods applicable to tall buildings. Tall buildings add complexity to the established procedures through the presence of the following test obstacles, not present in small buildings: larger envelope leakage area, inter-floor leakage, wind pressure, vertical shafts, and stack effect. These factors restrict the use of the established methods and require the development of a new method for tall buildings. The authors have developed the two test methods to perform this procedure, the floor-by-floor blower door method and the air handler method. These methods are new methods designed for specific application in tall buildings and are based on standard pressurization test methodology. The developed methods were tested on two large buildings.

The floor-by-floor blower door method procedure is intended to isolate a selected floor of a building to determine the envelope leakage rate associated with that test floor. This method proved to have conceptual merits, such as the ability to locate the vertical position of large envelope leakage. Unfortunately, its applicability to tall buildings is rather limited because sealing the shaft leakage may be an impossible task in some

buildings. Buildings with either floor-by-floor air handling units or through the wall ventilating units, both with limited vertical shafts, are ideal for the blower door testing method and seem to comprise the extent of its range of test buildings.

On the other hand, the air handler method has a wide range of applicability due to the nature of its design. This method uses the air handler fans to pressurize either a single building zone or the entire building. More often than not, tall buildings are designed with large centralized air handling units, thus providing the resource needed to pressurize the building zone. A number of flow measurement techniques can be used in the air handler method. The following techniques were chosen by the authors to measure the air flow through the fan based on their simplicity and general availability: tracer gas with recirculation, tracer gas with 100% outdoor air, orifice plate, and pitot tube traverse. These four flow measurement techniques provide the testing agency the opportunity to choose the simplest method for each particular application without large increases in the overall measurement uncertainty.

Many attempts were made to validate the floor-by-floor blower door method, but sealing the test floor from the adjacent floor and vertical building shafts proved to be an impossible task. Therefore, it was not possible to successfully apply this method to the building that was tested. It is the authors opinion that this method can be applied to tall buildings with small floor penetration area and accessibility to seal all the inter-floor leakage. If either of these two requirements is not met, then the air handler method should be performed.

The air handler method has a more general applicability and can be conducted in shorter amount of time than the floor-by-floor blower door method. The flow measurement techniques that were tested in this research were the tracer gas with recirculation, tracer gas with 100% outdoor air, and orifice plate. The flow rate estimates resulting from the tracer gas and orifice plate flow measuring techniques were not in agreement with each other at the Pattee East Library due to ongoing construction at the site that was being tested. The tracer gas test with 100% outdoor air flow resulted in a $Q_{50} = 9.61\ m^3/s$. The influence of the construction on the measured envelope leakage values can be seen in the orifice plate results, $Q_{50} = 31.39$. The two leakage test methods were tested at during separate phases of construction. The USX Tower was only tested with the tracer gas with 100% outdoor air method and resulted in $Q_{50} = 30.72\ m^3/s$.

The uncertainty in tracer gas flow rate measurement was completed by means of a root mean square error analysis, as described in Section 8.1. It was shown that the flow measurement has an uncertainty of 5.9% and 5.5% in the tracer gas with recirculation and the tracer gas with 100% outdoor air techniques, respectively. These flow rate uncertainties include a inter-zonal leakage estimate of 5%. Furthermore, the overall uncertainty in the flow rate at 50 Pascals, Q_{50}, was shown to be 3.0% to 3.8% depending on the wind velocity and the number of pressure taps used to average the pressure differential.

In addition to the two methods described in this project, general guidelines have been proposed to promote accurate estimates of building envelope leakage. The guidelines were established to reduce the uncertainty in the envelope leakage flow rate caused by

poor regression analysis, varying wind pressure, building orientation, and stack effect. The proposed guidelines have been drawn both from the existing standards and from experience gained in the course of this research. The general guidelines for conducting a pressurization test include:

To improve the precision of the regression analysis -

a. Minimum envelope pressure differential = 12.5 Pascals

b. Maximum envelope pressure differential = 75 Pascals

To reduce the effects of wind pressure due to wind speed and building orientation -

c. Maximum wind velocity = 4 m/s

To reduce the effects of stack effect -

d. Minimum outside temperature = 5 degrees Celsius

e. Maximum outside temperature = 35 degrees Celsius

The authors have shown through simulation that if the preceding set of guidelines are followed, the overall uncertainty in the estimate of the leakage flow rate at 50 Pascals, Q_{50}, can be as low as 3%. To date research on envelope leakage testing of tall buildings has been rather limited. Further research in this area is needed and should concentrate on testing the methods described herein on a large variety of tall buildings. Problems that arise or limitations of the methodology of the proposed test techniques should be described and possible solutions suggested. Further effort should devoted to establishing a consolidated database of leakage data as a reference for future leakage testing of tall buildings. To complete this task, a large number of buildings must be tested using the proposed techniques. The results of such a parametric study will provide additional insight into the overall accuracy of each leakage test technique while resulting in

additional comparison data. In the future, testing agencies could refer to this database to determine the relative leakage of the specific building being tested.

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Appendix A

Detailed Procedures for Field Testing of Tall Building to Determine Envelope Leakage Rate

Detailed Procedures for Field Testing of Tall Building to Determine Envelope Leakage Rate

This appendix is designed to assist a testing agency in conducting an envelope leakage test on a tall building. The set of guidelines established in this section detail the proper procedure to minimize error during the leakage testing. The following four test methods are described in full detail.

A-1.The Floor-by-Floor Method

A-2.The Air Handler Method using the Tracer Gas Flow Measurement Technique

A-2.1. With Recirculating Airflow

A-2.2. With 100% Outdoor Air

A-3.The Air Handler Method with Orifice Plate Flow Measuring Technique

A-4.The Air Handler Method with Pitot Traverse Flow Measuring Technique

The specific envelope leakage test procedure to be used in each application will be determined based on the properties of the building being tested. For more information refer to Chapters 8 and 9.

A-1 The Floor-by-Floor Method Testing Procedure

1. *Completely seal all interior leakage paths* that will allow air to travel from the testing floor to other building floors. This includes sealing all existing building openings such as stairwell doors, elevator doors, exhaust grilles and duct penetrations. Sealing can best be done in either of two methods. The first sealing procedure can be done by applying a non-porous adhesive to the crack, such putting duct tape over the intersection and perimeter of elevator doors. The second procedure uses a non-porous

tape to adhere a plastic sheeting to cover a larger surface area. The plastic sheeting is especially useful when covering both return and supply grilles.

Central Air Handling System: In a building with a central air distribution system, the ducts should be sealed as close to the supply and return risers as possible to prevent any duct leakage from influencing the test floor.

2. *Open all interior doors* on the upper, lower, and testing floor to allow for a nearly equal pressure across the floor, ceiling, and exterior envelope.
3. *Set up the blower door(s)* device in a stairwell door or an operable window on the test floor. If the blower door is set up in a stairwell be sure to open the exterior stairwell doors to avoid depressurizing the stairwell.
4. *Pressurize the adjacent floors.* This can be done either with the building/zone air handling system or with additional blower doors located on the upper and lower floors. If blower doors are used they should be located in other stairwells, to assure a good air supply for each floor, or in an operable window. Additionally, placing the blower doors in other stairwells will avoid any influence of test floor flow adjustments on the pressures of the adjacent floors. A much larger flow will be needed through these fans than through the test floor fans since air will escape to the other floors of the building. If constant speed blower door fans are used, the pressure can be maintained by adjusting the stairwell doors, without the test floor blower door, on the adjacent floors. In the situation where additional air flow is needed on the adjacent floors, more than one blower door can be set up in the other stairwells or the adjacent floors can be sealed to reduce air leakage to internal air paths.

Central Air Handling System When the building air handling system is used to pressurize the adjacent floors, the exhaust, outdoor, and return air dampers can be adjusted to maintain the desired pressure in the upper and lower floors, as described in the note following Figure A1. In a variable air volume system, the fan speed or inlet vanes can be adjusted to vary the air flow to the adjacent floors. If the pressure is not equal on the two adjacent floors, a stairwell door (not the one containing the blower door) on the floor of higher pressure can be partially opened to equalize the pressure. With this pressurization technique, it is imperative that the seals on the supply and return duct penetrations on the test floor be strong enough to hold the force of the pressure within the duct. In this air handler configuration the return fan

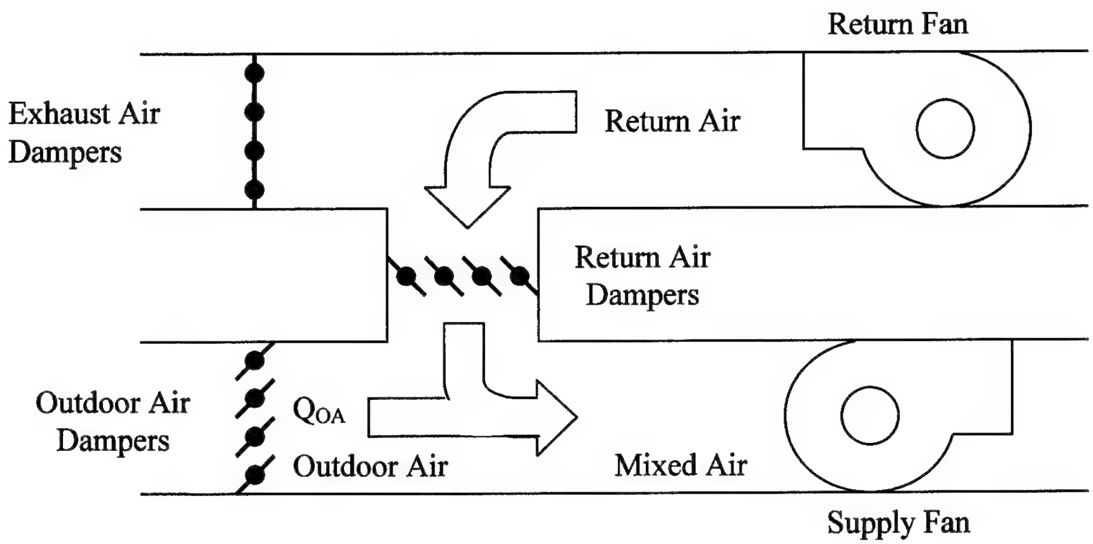


Figure A1 – Typical Air Handling Unit

Note: To maintain a fixed pressure in the space, close and seal the Exhaust Air Damper and modulate the Return and Outdoor Air Dampers. This can easily be done by adjusting the set point temperature of the mixed air.

can either be turned on or off to lower or raise the pressure on the adjacent floors.

Floor-by-Floor Air Handling System In a building with floor-by-floor air handling systems, the pressures on the two adjacent floors can be maintained by adjusting the damper settings on each individual floor as described above for the building air handling unit.

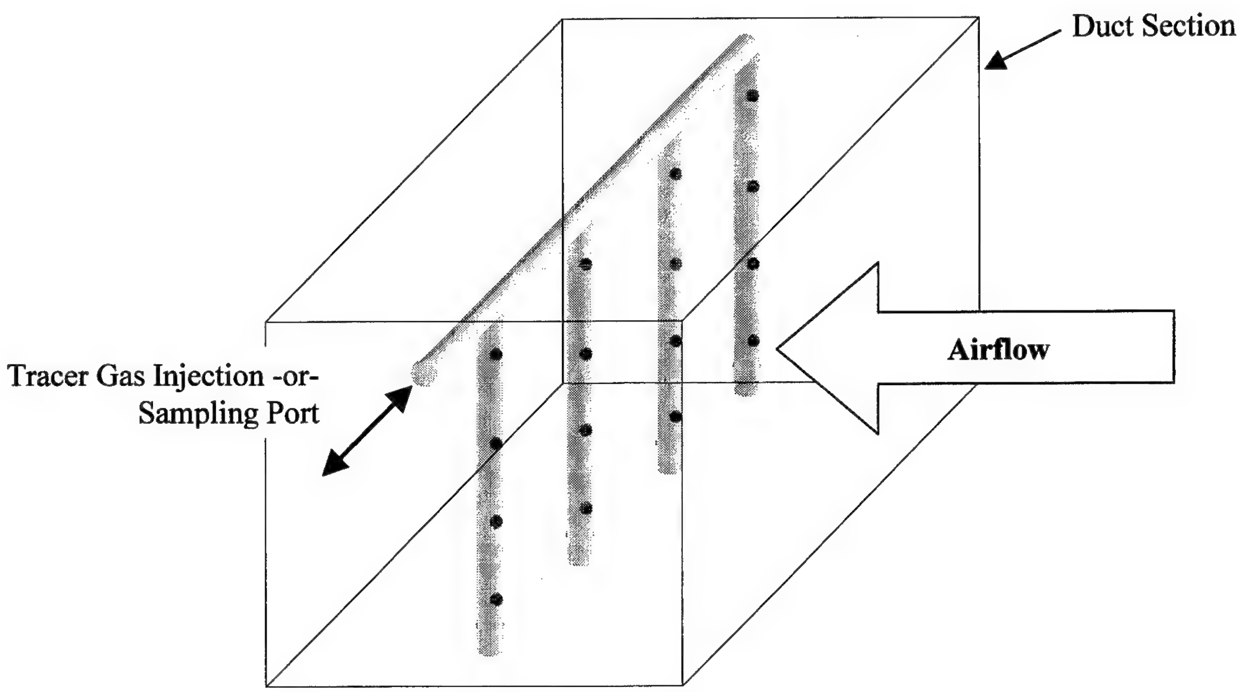
5. *Run a blower door test matching the pressures on the test floor and the two adjacent floors.* Some blower doors have accompanying software that will automatically read and record the airflow and pressures differential between the floor and outdoor air pressure of each test. Otherwise, the airflow and pressure will have to be measured and recorded separately.

6. *Adjust the pressures on the adjacent and test floors and repeat the test.* Continue to repeat the test at a series of five different zone pressure differential readings. Test results should be tested for repeatability by re-running the test at various floor pressures and comparing the results

A-2 The Air Handler Method using the Tracer Gas Flow Measurement Technique Testing Procedure

A-2.1 Tracer Gas with Recirculating Air Flow - Testing Procedure

1. *Close and seal all return air dampers* to prevent any air from escaping through the air handling system. It is recommended that non-porous tape be used to adhere a plastic sheeting to cover return grilles. This sealing procedure is can be quickly completed once the plastic sheeting has been cut to size. The plastic sheets should not be discarded after each test, as many return air dampers in buildings have similar areas.
2. *Install the tracer gas supply device (S) and the three concentration (CRet1, CRet2, CSup) sampling grids in the locations shown in Figure A3.*



<u>Figure A2 – Tracer Gas Injection / Sampling Manifold</u>
The tracer gas manifold shown above can be used as either and injection or sampling grid. The tracer gas manifold has pin sized orifices that allow the gas to be evenly injected or sampled across the cross section of the duct.

The tracer gas supply device should be spaced far enough from C_{Ret1} to prevent any backflow or eddies from altering the true concentrations in the air returning to the test zone. In our experiments twenty feet upstream in a straight duct section eliminated any possibility of short circuiting the tracer gas. A potential problem to be avoided is a non-uniform dispersion of the tracer gas in the air handler. To be sure the gas is well mixed, both injection and withdrawal grids, shown in Figure A2, should be used to supply and sample the tracer gas concentration throughout the cross section of the duct. The best way to ensure a uniform dispersion of tracer gas across the duct is to design a manifold that will create an equal pressure drop across all the dispersion holes. Conduct a series of sample tracer gas concentration tests downstream of the supply grid and compare the results. The results should remain constant, and using a similar withdrawal grid will further reduce the error caused by non-uniform tracer gas dispersion in the duct.

3. *Layout four, equally spaced pressure taps on each face of the building for each floor in the test zone and the two neighboring floors.* Each pressure tap should be a representative measure of an equal area of the building envelope. The pressure tap should be provided at the mid-height of the floor being tested. To obtain the correct indoor-outdoor pressure differential at each location, a capillary tube must be driven through the building envelope. To insert the tube either a hole must be drilled through the wall or the tube must be inserted into an existing opening.
4. *Adjust the return and outdoor air dampers to maintain the desired pressure in the building or air handler zone,* 12.5, 25, 37.5, 50, 62.5, 75 Pa (adopted from the ASTM Standard E779). If the pressurization fans are unable to pressurize the test space to a

maximum pressure of 75 Pa then select six equally spaced pressure measurements from 12.5 to the max test pressure.

5. *Measure the pressure differential* across each face of the building on every floor in the test zone plus the floors both directly above and below the test zone, if any. Inspect the measurements to be sure that the pressure is maintained in the building.
6. *If there is more than one air handler zone, adjust the pressures in the adjacent air handler zones* in a similar manner to negate a pressure drop across the indoor perimeter of the testing zone.
7. *Adjust the zone pressure differential by lowering the fan air flow and repeat the test.* Continue to repeat the test at the series pressure differentials listed above in step 4. Test results should be tested for repeatability by re-running the test at various floor pressures and comparing the results

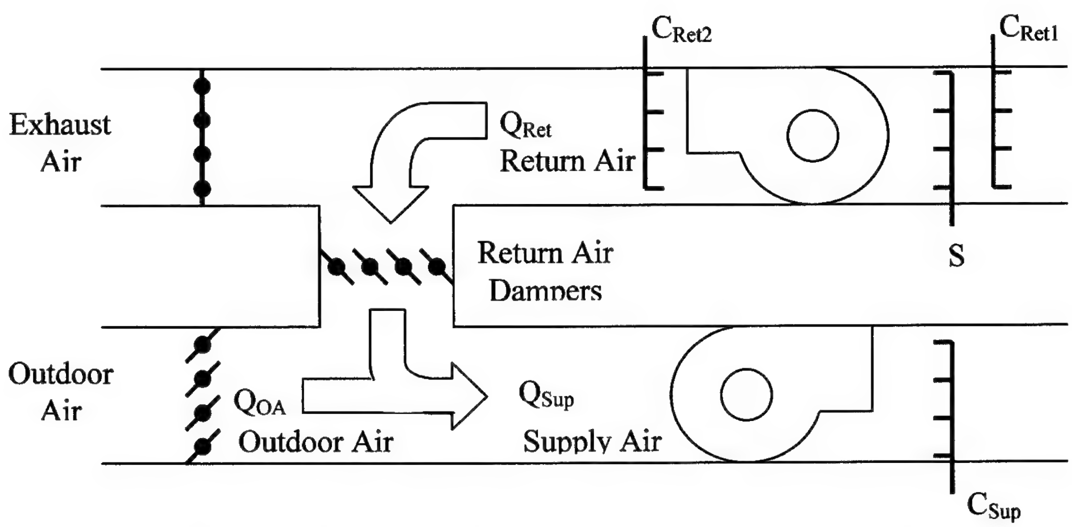


Figure A3 – Tracer Gas Method with Recirculating Air

Tracer Gas Method with Recirculating Air requires three Concentration Sensors, C_x, and one Supply Injection Grid, S.

A-2.2 Tracer Gas with 100% Outdoor Air - Testing Procedure

1. Close and seal the exhaust and return air dampers to prevent any air from leaking through the air handling system. This can be best accomplished by covering the damper with a plastic sheet and allowing the pressure from the ductwork to keep it in place.

2. Place the tracer gas supply device, S, and the concentration sensor, C_{Sup}, in the locations shown in Figure A4.

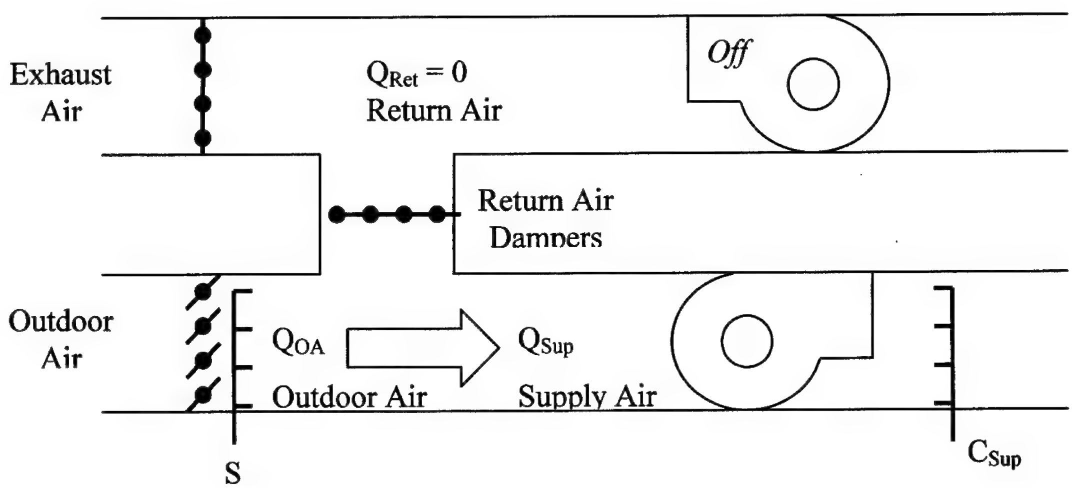


Figure A4 – Tracer Gas Method without Recirculating Air
The Tracer Gas Method with 100% outdoor air requires only 1 Concentration Sensor, C_{Sup}, and 1 Supply Injection Grid, S.

3. *Layout four, equally spaced pressure taps on each face of the building for each floor in the test zone and the two neighboring floors.* Each pressure tap should be a representative measure of an equal area of the building envelope. The pressure tap should be provided at the mid-height of the floor being tested. To obtain the correct indoor-outdoor pressure differential at each location, a capillary tube must be driven through the building envelope. To insert the tube either a hole must be drilled through the wall or the tube must be inserted into an existing opening.

4. Set the building to the desired pressure, 12.5 to 75 Pa, by adjusting either:

    1. the outdoor air dampers,

    2. the vortex damper on the supply air fan, or

    3. the variable speed drive on the supply fan.

    Record the pressures in the building throughout the test, and inspect them to be sure that the pressure is maintained in the building. If the pressurization fans are unable to pressurize the test space to a maximum pressure of 75 Pa then select six equally spaced pressure measurements from 12.5 to the max test pressure.

5. Test results should be tested for repeatability by re-running the test at various floor pressures under similar conditions. The test should be repeated until a well-developed pattern emerges that can be accurately correlated.

A-3 The Air Handler Method with Orifice Plate Flow Measurement Technique Testing Procedure

1. *Close and seal the exhaust air damper* to prevent any air from leaking out through the air handling system. The return air damper may or may not be closed and sealed at this time and it is dependent on the pressure range within the building. If the range of test pressures, 12.5 to 75 Pa, can be met with the return air damper sealed, it is advisable to seal it. If the low end of the pressure range cannot be achieved, then the return air damper must be opened.
2. *Install the orifice plate and vinyl sheet over the outdoor air grille*, sealing it entirely except for the hole in the orifice plate. The orifice plate must be installed in a position on the outdoor air grille to receive unobstructed air flow. To comply with this requirement, the orifice plate should be installed as far from any building or landscaping interference (i.e. overhangs, exterior building walls, trees, etc.). If unobstructed air flow is not possible, the orifice plate must be calibrated in its testing position. This calibration technique is a recommended even if unobstructed air flow is present.
3. *Calibrate the orifice plate* using a pitot-static tube, tracer gas technique, or other velocity measuring device. The calibration will set the relationship between the outdoor air entering the air handler, to the pressure drop across the face of the orifice plate. Measure both the velocity of the air traveling through the orifice and the pressure drop across the plate. Calculate the total outdoor air flow, using the average

velocity and the orifice diameter. The flow characteristics of the orifice place can be calculated using Equation A-3.1 below.

$$C = \sqrt{\frac{V^2}{2g_c * \Delta P / \rho}} \qquad \text{(A-3.1)}$$

where,

C = Discharge coefficient (dimensionless)

V = Velocity through the plate (m/s)

g_c = 1.0 (kg-m)/(N-s^2)

P = Pressure across the plate (Pa)

ρ = Air density (kg/m^3)

(Note: The outdoor air flow entering through the orifice plate must be uniform and undisturbed to use the standard orifice plate discharge coefficient of 0.61.) After the orifice plate has been calibrated, it is only necessary to measure the pressure difference across the plate for each succeeding reading.

4. *Layout four, equally spaced pressure taps on each face of the building for each floor in the test zone and the two neighboring floors.* Each pressure tap should be a representative measure of an equal area of the building envelope. The pressure tap should be provided at the mid-height of the floor being tested. To obtain the correct indoor-outdoor pressure differential at each location, a capillary tube must be driven through the building envelope. To insert the tube either a hole must be drilled through the wall or the tube must be inserted into an existing opening.
5. Set the building to the desired pressure, 12.5 to 75 Pa, by adjusting either:

1. the outdoor air dampers,
2. the vortex damper on the supply air fan, or
3. the variable speed drive on the supply fan.

Record the pressures in the building throughout the test, and inspect them to be sure that the pressure is maintained in the building. If the pressurization fans are unable to pressurize the test space to a maximum pressure of 75 Pa then select six equally spaced pressure measurements from 12.5 to the max test pressure.

5. *Record the measure the pressure differential across the orifice plate.*
6. *Adjust the zone pressure differential by lowering the fan air flow and repeat the test.* Continue to repeat the test until all six target pressures are met. Test results should be tested for repeatability by re-running the test at various floor pressures under similar conditions. The test should be repeated until a well-developed pattern emerges that can be accurately correlated.

A-4 The Air Handler Method with Pitot Tube Traverse Flow Measurement Technique Testing Procedure

1. *Close and seal the exhaust air damper* to prevent any air from leaking out through the air handling system. (The return air damper may or may not be closed and sealed at this time.)

2. *Layout four, equally spaced pressure taps on each face of the building for each floor in the test zone and the two neighboring floors.* Each pressure tap should be a representative measure of an equal area of the building envelope. The pressure tap should be provided at the mid-height of the floor being tested. To obtain the correct indoor-outdoor pressure differential at each location, a capillary tube must be driven through the building envelope. To insert the tube either a hole must be drilled through the wall or the tube must be inserted into an existing opening.

6. Set the building to the desired pressure, 12.5 to 75 Pa, by adjusting either:

   1. the outdoor air dampers,
   2. the vortex damper on the supply air fan, or
   3. the variable speed drive on the supply fan.

   Record the pressures in the building throughout the test, and inspect them to be sure that the pressure is maintained in the building. If the pressurization fans are unable to pressurize the test space to a maximum pressure of 75 Pa then select six equally spaced pressure measurements from 12.5 to the max test pressure.

3. *Conduct a velocity traverse downstream of the supply fan before any duct branches.* It is imperative that the flow be straight at the point of testing. (It is recommended that at least 75 percent of the velocity measurements across the traverse are at least 10

percent of the maximum velocity (AMCA 1976).) If recirculated air is being used, a velocity traverse must be completed in the return duct also.

4. *Adjust the zone pressure differential by lowering the fan air flow and repeat the test.* Continue to repeat the test until all six target pressures have been tested. Test results should be tested for repeatability by re-running the test at various floor pressures under similar conditions. The test should be repeated until a well-developed pattern emerges that can be accurately correlated.

Appendix B

Orifice Plate Results and Analysis for Pattee East Library

Appendix B

Orifice Plate Results and Analysis Using the Engineering Equation Solver

B-1.1 The Orifice Plate Calibration

The program Flow Analysis, provided below, is a system of simultaneous equations that ultimately solves for the orifice plate discharge coefficient using Equation 4.8. Velocity measurements were made with velocity grid approximately 4 inches below the edge of the plate. (Note: A pitot tube was used only during the first test on May 21. The velocity equations indicate a an average velocity across equal areas of the plate) The individual velocity measurements are entered into the velocity equations, V_xxN or V_xxS. The C, N, E, S, W indicate where the velocity grid was positioned in the plate: Center, North, East, South, West, respectively. Overlapping the areas within the orifice plate was permitted since the velocity grid was returning the average velocity over a 14" x 14" area. The flow through the plate was calculated using the known area of the opening. The differential pressure across the plate was also measured and is listed in the P_xxavg equation. This equation calculated the average pressure across the plate. Using the average pressure and velocity, a discharge coefficient was found for each test run. The average discharge coefficient for the plate was calculated by averaging the individual test run coefficients. This procedure was completed for both orifice plates, and for the three test dates.

B1.1.1 Orifice Plate Calibration for 21 May

```
"Flow Analysis -        Test Date:  21 May 1997"

"Test 1 - 21 May 1997"
"Plate 1"
V_111=(2709+2704+2700+2783+2761+2742)/6
V_112=(2953+3017+2894+2943+2912+2988)/6
V_113=(3093+3096+3108+3133+3119+3052)/6
V_114=(3467+3480+3471+3413+3347+3382)/6
V_115=(3581+3433+3523+3611+3315+3371)/6
V_116=(2776+2662+2746+2771+2686+2968)/6

V_11avg=(V_111+V_112+V_113+V_114+V_115+V_116)/6

Q_11avg=3.1416*(1.5^2)*(V_11avg)

P_11avg=(254.9+253.5+260.4+258+261.3+256.6+255.3+249.7)/8

C_11=(((V_11avg/60)^2)/((2*32.17*(P_11avg/47.88))/0.0827))^0.5
```

```
"Plate 2"
V_121=(2818+2806+2816+2883+2941+2909)/6
V_122=(2929+2952+2936+2961+2911+2961)/6
V_123=(3095+3109+3057+2993+3011+3048)/6
V_124=(3213+3155+3175+3216+3197+3167)/6
V_125=(3247+3361+3283+3237+3289+3425)/6
V_126=(3463+3507+3495+3529+3471+3474)/6

V_12avg=(V_121+V_122+V_123+V_124+V_125+V_126)/6

Q_12avg=3.1416*(1.5^2)*(V_12avg)

P_12avg=(254.9+253.5+260.4+258+261.3+256.6+255.3+249.7)/8

C_12=(((V_12avg/60)^2)/((2*32.17*(P_12avg/47.88))/0.0827))^0.5

"Test 2 - 21 May 1997"
"Plate 1"
V_21C=(2188+2172)/2
V_21N=(2257+2240)/2
V_21E=(2250+2268)/2
V_21S=(2184+2198)/2
V_21W=(2233+2238)/2
V_21avg=(V_21C+V_21N+V_21E+V_21S+V_21W)/5

Q_21avg=3.1416*(1.5^2)*(V_21avg)

P_21avg=(117.7+120.1+117.8+119.5+120.9+115.3+118.3)/7

C_21=(((V_21avg/60)^2)/((2*32.17*(P_21avg/47.88))/0.0827))^0.5

"Plate 2"
V_22C=(2353+2368)/2
V_22N=(2335+2356)/2
V_22E=(2415+2435)/2
V_22S=(2461+2440)/2
V_22W=(2252+2240)/2
V_22avg=(V_22C+V_22N+V_22E+V_22S+V_22W)/5

Q_22avg=3.1416*(1.5^2)*(V_22avg)

P_22avg=(117.7+120.1+117.8+119.5+120.9+115.3+118.3)/7

C_22=(((V_22avg/60)^2)/((2*32.17*(P_22avg/47.88))/0.0827))^0.5

"Test 3 - 21 May 1997"
```

```
"Plate 1"
V_31C=(1699+1717)/2
V_31N=(1707+1690)/2
V_31E=(1728+1720)/2
V_31S=(1714+1733)/2
V_31W=(1694+1713)/2
V_31avg=(V_31C+V_31N+V_31E+V_31S+V_31W)/5

Q_31avg=3.1416*(1.5^2)*(V_31avg)

P_31avg=(74.28+72.45+73.9+72.55+73.21+75.01+74.37+73.83)/8

C_31=(((V_31avg/60)^2)/((2*32.17*(P_31avg/47.88))/0.0827))^0.5

"Plate 2"
V_32C=(1822+1842)/2
V_32N=(1742+1738)/2
V_32E=(1785+1814)/2
V_32S=(1764+1746)/2
V_32W=(1738+1748)/2
V_32avg=(V_32C+V_32N+V_32E+V_32S+V_32W)/5

Q_32avg=3.1416*(1.5^2)*(V_32avg)

P_32avg=(74.28+72.45+73.9+72.55+73.21+75.01+74.37+73.83)/8

C_32=(((V_32avg/60)^2)/((2*32.17*(P_32avg/47.88))/0.0827))^0.5

"Test 4 - 21 May 1997"
"Plate 1"
V_41C=(1122+1131)/2
V_41N=(1053+1061)/2
V_41E=(1109+1096)/2
V_41S=(1094+1100)/2
V_41W=(1076+1076)/2
V_41avg=(V_41C+V_41N+V_41E+V_41S+V_41W)/5

Q_41avg=3.1416*(1.5^2)*(V_41avg)

P_41avg=(32.48+31.64+30.74+31.02+31.17+31.9+31.5+31.58)/8

C_41=(((V_41avg/60)^2)/((2*32.17*(P_41avg/47.88))/0.0827))^0.5

"Plate 2"
V_42C=(1204+1206)/2
V_42N=(1193+1196)/2
```

```
V_42E=(1146+1138)/2
V_42S=(1163+1175)/2
V_42W=(1141+1136)/2
V_42avg=(V_42C+V_42N+V_42E+V_42S+V_42W)/5

Q_42avg=3.1416*(1.5^2)*(V_42avg)

P_42avg=(32.48+31.64+30.74+31.02+31.17+31.9+31.5+31.58)/8

C_42=(((V_41avg/60)^2)/((2*32.17*(P_41avg/47.88))/0.0827))^0.5


"Average C Value"

C_1= (C_11+C_21+C_31+C_41)/4
C_2= (C_12+C_22+C_32+C_42)/4
```

B1.1.2 Orifice Plate Calibration for 28 May

"Flow Analysis - Test Date: 28 May 1997"

"Test 3 - 28 May 1997"
"Plate 1"
V_31C=(2264+2291+2281+2268)/4
V_31N=(2379+2371+2352+2368)/4
V_31E=(2314+2334+2329+2306)/4
V_31S=(2353+2365+2354+2343)/4
V_31W=(2296+2282+2298+2269)/4
V_31avg=(V_31C+V_31N+V_31E+V_31S+V_31W)/5

Q_31avg=3.1416*(1.5^2)*(V_31avg)

P_31avg=(130.8+138.3+133.4+133.9+135.6+131.7+135.6+131.6+132.3)/9

C_31=(((V_31avg/60)^2)/((2*32.17*(P_31avg/47.88))/0.0827))^0.5

"Plate 2"
V_32C=(2332+2296+2340+2310)/4
V_32N=(2338+2372+2323+2330)/4
V_32E=(2381+2367+2370+2333)/4
V_32S=(2410+2394+2353+2400)/4
V_32W=(2273+2252+2277+2287)/4
V_32avg=(V_32C+V_32N+V_32E+V_32S+V_32W)/5

Q_32avg=3.1416*(1.5^2)*(V_32avg)

P_32avg=(130.8+138.3+133.4+133.9+135.6+131.7+135.6+131.6+132.3)/9

C_32=(((V_32avg/60)^2)/((2*32.17*(P_32avg/47.88))/0.0827))^0.5

"Test 4 - 28 May 1997"
"Plate 1"
V_41C=(1651+1664+1652+1657)/4
V_41N=(1679+1667+1665+1691)/4
V_41E=(1663+1679+1671+1661)/4
V_41S=(1694+1688+1716+1707)/4
V_41W=(1660+1653+1677+1665)/4
V_41avg=(V_41C+V_41N+V_41E+V_41S+V_41W)/5

Q_41avg=3.1416*(1.5^2)*(V_41avg)

P_41avg=(73.38+72.07+71.72+75.15+73.91+73.17+73.7+73.31+72.04)/9

C_41=(((V_41avg/60)^2)/((2*32.17*(P_41avg/47.88))/0.0827))^0.5

```
"Plate 2"
V_42C=(1719+1717+1717+1720)/4
V_42N=(1745+1739+1746+1754)/4
V_42E=(1772+1761+1754+1744)/4
V_42S=(1778+1795+1789+1767)/4
V_42W=(1646+1665+1674+1667)/4
V_42avg=(V_42C+V_42N+V_42E+V_42S+V_42W)/5

Q_42avg=3.1416*(1.5^2)*(V_42avg)

P_42avg=(73.38+72.07+71.72+75.15+73.91+73.17+73.7+73.31+72.04)/9

C_42=(((V_42avg/60)^2)/((2*32.17*(P_42avg/47.88))/0.0827))^0.5

"Test 5 - 28 May 1997"
"Plate 1"
V_51C=(1336+1333+1307+1344)/4
V_51N=(1398+1354+1364+1360)/4
V_51E=(1327+1341+1327+1335)/4
V_51S=(1338+1321+1333+1319)/4
V_51W=(1287+1289+1319+1290)/4
V_51avg=(V_51C+V_51N+V_51E+V_51S+V_51W)/5

Q_51avg=3.1416*(1.5^2)*(V_51avg)

P_51avg=(45.98+44.57+45.52+45.72+46+44.45+44.96+43.83+44.42)/9

C_51=(((V_51avg/60)^2)/((2*32.17*(P_51avg/47.88))/0.0827))^0.5

"Plate 2"
V_52C=(1358+1341+1368+1364)/4
V_52N=(1362+1387+1353+1354)/4
V_52E=(1383+1382+1418+1393)/4
V_52S=(1379+1375+1376+1390)/4
V_52W=(1325+1345+1342+1352)/4
V_52avg=(V_52C+V_52N+V_52E+V_52S+V_52W)/5

Q_52avg=3.1416*(1.5^2)*(V_52avg)

P_52avg=(45.98+44.57+45.52+45.72+46+44.45+44.96+43.83+44.42)/9

C_52=(((V_52avg/60)^2)/((2*32.17*(P_52avg/47.88))/0.0827))^0.5

"Test 6 - 28 May 1997"
"Plate 1"
```

```
V_61C=(1105+1112+1106+1129)/4
V_61N=(1150+1128+1161+1157)/4
V_61E=(1075+1139+1191+1186)/4
V_61S=(1104+1109+1069+1087)/4
V_61W=(1097+1097+1068+1057)/4
V_61avg=(V_61C+V_61N+V_61E+V_61S+V_61W)/5

Q_61avg=3.1416*(1.5^2)*(V_61avg)

P_61avg=(33.98+32.3+32.97+32.53+33.25+33.29+33.87+32.42)/8

C_61=(((V_61avg/60)^2)/((2*32.17*(P_61avg/47.88))/0.0827))^0.5

"Plate 2"
V_62C=(1163+1184+1147+1169)/4
V_62N=(1153+1195+1201+1194)/4
V_62E=(1144+1236+1164+1187)/4
V_62S=(1184+1156+1158+1177)/4
V_62W=(1081+1071+1091+1087)/4
V_62avg=(V_62C+V_62N+V_62E+V_62S+V_62W)/5

Q_62avg=3.1416*(1.5^2)*(V_62avg)

P_62avg=(33.98+32.3+32.97+32.53+33.25+33.29+33.87+32.42)/8

C_62=(((V_62avg/60)^2)/((2*32.17*(P_62avg/47.88))/0.0827))^0.5

"Average C Value"

C_1= (C_31+C_41+C_51+C_61)/4
C_2= (C_32+C_42+C_52+C_62)/4
```

B1.1.3 Orifice Plate Calibration for 29 May

"Flow Analysis - Test Date: 29 May 1997"

"Test 3 - 29 May 1997"
"Plate 1"
V_31C=(2247+2284+2250+2259+2210)/5
V_31N=(2219+2232+2232+2241+2240)/5
V_31E=(2282+2286+2305+2305+2290)/5
V_31S=(2307+2249+2301+2283+2284)/5
V_31W=(2308+2333+2354+2339+2350)/5

V_31avg=(V_31C+V_31N+V_31E+V_31S+V_31W)/5

Q_31avg=3.1416*(1.5^2)*(V_31avg)

P_31avg=(122.8+123.1+124.4+122.3+124.5+120.1+120.8+122.5+124.9)/9

C_31=(((V_31avg/60)^2)/((2*32.17*(P_31avg/47.88))/0.0827))^0.5

"Plate 2"
V_32C=(2296+2298+2314+2314+2306)/5
V_32N=(2271+2299+2293+2340+2312)/5
V_32E=(2315+2371+2310+2374+2358)/5
V_32S=(2342+2435+2384+2314+2373)/5
V_32W=(2218+2178+2176+2243+2197)/5
V_32avg=(V_32C+V_32N+V_32E+V_32S+V_32W)/5

Q_32avg=3.1416*(1.5^2)*(V_32avg)

P_32avg=(122.8+123.1+124.4+122.3+124.5+120.1+120.8+122.5+124.9)/9

C_32=(((V_32avg/60)^2)/((2*32.17*(P_32avg/47.88))/0.0827))^0.5

"Test 4 - 29 May 1997"
"Plate 1"
V_41C=(1992+2001+1983+1998+1980)/5
V_41N=(2018+2004+2056+2022+1991)/5
V_41E=(1971+2001+2001+1991+2003)/5
V_41S=(1996+1998+2016+2052+2046)/5
V_41W=(2020+2034+2004+2036+1987)/5
V_41avg=(V_41C+V_41N+V_41E+V_41S+V_41W)/5

Q_41avg=3.1416*(1.5^2)*(V_41avg)

P_41avg=(93.31+96.23+93.23+96.41+98.06+95.88+98.84+97.08+97.16)/9

C_41=(((V_41avg/60)^2)/((2*32.17*(P_41avg/47.88))/0.0827))^0.5

"Plate 2"
V_42C=(2057+2001+2074+2085+2057)/5
V_42N=(2051+2085+2088+2124+2135)/5
V_42E=(2098+2106+2068+2087+2090)/5
V_42S=(2115+2115+2111+2115+2131)/5
V_42W=(2003+1992+1984+2003+2005)/5
V_42avg=(V_42C+V_42N+V_42E+V_42S+V_42W)/5

Q_42avg=3.1416*(1.5^2)*(V_42avg)

P_42avg=(93.31+96.23+93.23+96.41+98.06+95.88+98.84+97.08+97.16)/9

C_42=(((V_42avg/60)^2)/((2*32.17*(P_42avg/47.88))/0.0827))^0.5

"Test 5 - 29 May 1997"
"Plate 1"
V_51C=(1665+1669+1664+1666+1645)/5
V_51N=(1659+1653+1647+1629+1636)/5
V_51E=(1662+1609+1674+1631+1604)/5
V_51S=(1695+1710+1734+1736+1705)/5
V_51W=(1703+1714+1686+1672+1684)/5
V_51avg=(V_51C+V_51N+V_51E+V_51S+V_51W)/5

Q_51avg=3.1416*(1.5^2)*(V_51avg)

P_51avg=(67.07+65.14+66.89+70.5+68.21+67.71+65.92+68.07+68.07+67.22)/10

C_51=(((V_51avg/60)^2)/((2*32.17*(P_51avg/47.88))/0.0827))^0.5

"Plate 2"
V_52C=(1671+1664+1674+1705+1713)/5
V_52N=(1782+1781+1763+1767+1786)/5
V_52E=(1764+1732+1724+1741+1745)/5
V_52S=(1750+1763+1738+1748+1712)/5
V_52W=(1645+1690+1634+1647+1688)/5
V_52avg=(V_52C+V_52N+V_52E+V_52S+V_52W)/5

Q_52avg=3.1416*(1.5^2)*(V_52avg)

P_52avg=(67.07+65.14+66.89+70.5+68.21+67.71+65.92+68.07+68.07+67.22)/10

C_52=(((V_52avg/60)^2)/((2*32.17*(P_52avg/47.88))/0.0827))^0.5

"Test 6 - 29 May 1997"

"Plate 1"
V_61C=(2073+2049+2045+2097+2058)/5
V_61N=(2045+2089+2055+2073+2081)/5
V_61E=(2092+2101+2079+2095+2081)/5
V_61S=(2088+2095+2109+2076+2091)/5
V_61W=(2050+2022+2102+2067+2053)/5
V_61avg=(V_61C+V_61N+V_61E+V_61S+V_61W)/5

Q_61avg=3.1416*(1.5^2)*(V_61avg)

P_61avg=(102+99.1+100.6+102.3+100.9+101.2+101.7+103.8+101.2)/9

C_61=(((V_61avg/60)^2)/((2*32.17*(P_61avg/47.88))/0.0827))^0.5

"Plate 2"
"Plate 2 was not used for this test"

"Average C Value"

C_1= (C_31+C_41+C_51+C_61)/4
C_2= (C_32+C_42+C_52)/3

B1.2 Solving the Power Law Equation by Minimizing RMS Error

The set of equations listed below is titled "Error Analysis," but this actually refers to minimizing the root mean square error produce by selecting the best fit C value for a given range of "n" values. This is explained in full detail in Section 6.2. The differential pressure measurements across the building floors are averaged and input into the P_xy variable. The x indicates the test run and the y is the floor corresponding to the recorded pressure. The actual outdoor air flow was determined in the orifice plate calibration and is designated Q_xact. The predicted airflow, Q_xpred, is the value which is being set equal to the actual airflow. Q_xpred is based on Equation 13 and uses the average pressure previously described. The solution is set to minimize the total error, Error_tot, for a given n value, by selecting C. The solutions to the test runs for each day follow the equation list.

B1.2.1a Solving for C and n - Equations (21 May)

```
"Error Analysis -       Test Date:  21 May 1997"
"Plate Coefficients Data from 21Flow.ees"
C_1=.817
C_2=.828

"Test 1 - 21 May 1997 "
P_11=35
P_12=36
P_13=38
P_14=41
P_15=42

Q_1act=43933

Q_1pred=C*((P_11^n)+(P_12^n)+(P_13^n)+(P_14^n)+(P_15^n))

Error_1=((Q_1act-Q_1pred)^2)^.5

"Test 2 - 21 May 1997"
P_21=26.5
P_22=28.5
P_23=30.5
P_24=34.5
P_25=36

Q_2act=32433

Q_2pred=C*((P_21^n)+(P_22^n)+(P_23^n)+(P_24^n)+(P_25^n))
```

```
Error_2=((Q_2act-Q_2pred)^2)^.5

"Test 3 - 21 May 1997"
P_31=21
P_32=23.5
P_33=27
P_34=29
P_35=31

Q_3act=24637

Q_3pred=C*((P_31^n)+(P_32^n)+(P_33^n)+(P_34^n)+(P_35^n))

Error_3=((Q_3act-Q_3pred)^2)^.5

"Test 4 - 21 May 1997"
P_41=14
P_42=17
P_43=20
P_44=21.5
P_45=23.5

Q_4act=15986

Q_4pred=C*((P_41^n)+(P_42^n)+(P_43^n)+(P_44^n)+(P_45^n))

Error_4=((Q_4act-Q_4pred)^2)^.5

"Total Error"
Error_Tot=(Error_1^2+Error_2^2+Error_3^2+Error_4^2)^0.5
```

B1.2.1b Solving for C and n - Solutions (21 May)

n	C	Total Error
0.40	1500.0	14953
0.42	1477.0	14359
0.44	1382.0	14069
0.46	1293.0	13779
0.48	1209.6	13489
0.50	1131.5	13200
0.52	1058.4	12912
0.54	989.9	12625
0.56	925.8	12339
0.58	865.8	12053
0.60	809.6	11768
0.62	756.9	11484
0.64	707.7	11200
0.66	661.6	10918
0.68	618.5	10636
0.70	578.1	10355
0.72	540.3	10075
0.74	505.0	9796
0.76	471.9	9518
0.78	441.0	9241
0.80	412.1	8965
0.82	385.0	8690
0.84	359.7	8416
0.86	336.0	8143
0.88	313.9	7871
0.90	293.2	7600
0.92	273.9	7330
0.94	255.8	7061
0.96	238.9	6793
0.98	223.1	6526
1.00	208.3	6261
1.02	194.5	5996
1.04	181.6	5733
1.06	169.5	5471
1.08	158.3	5210
1.10	147.7	4951
1.12	137.9	4693
1.14	128.7	4436
1.16	120.1	4180
1.18	112.1	3926

n	C	Total Error
1.20	104.6	3673
1.22	97.6	3422
1.24	91.1	3172
1.26	85.0	2924
1.28	79.3	2678
1.30	74.0	2434
1.32	69.0	2192
1.34	64.4	1953
1.36	60.1	1718
1.38	55.9	1490
1.40	52.3	1261
1.42	48.7	1046
1.44	45.5	846
1.46	42.4	673
1.48	39.5	554
1.50	36.9	524
1.52	34.4	595
1.54	32.0	737
1.56	29.9	917
1.58	27.9	1116
1.60	26.0	1325
1.62	24.2	1539
1.64	22.6	1755
1.66	21.0	1974
1.68	19.6	2193
1.70	18.3	2412
1.72	17.0	2631
1.74	15.9	2849
1.76	14.8	3067
1.78	13.8	3284
1.80	12.8	3500
1.82	12.0	3716
1.84	11.2	3930
1.86	10.4	4144
1.88	9.7	4356
1.90	9.0	4567
1.92	8.4	4777
1.94	7.8	4987
1.96	7.3	5195
1.98	6.8	5402

Table B1 - Determining C and n by Minimizing Total Error (21 May 1997)

B1.2.2a Solving for C and n - Equations (28 May)

```
"Error Analysis -	Test Date: 28 May 1997"
"Discharge Coefficients were determined using the Flow.ees program and are used to
find the actual flow in Tests 1 and 2"
C_1=0.815
C_2=0.837

"Test 1 - 28 May 1997
No Flow Measurements - Velocity was too high across the plate to "
P_11=33
P_12=34.5
P_13=36.5
P_14=38
P_15=38

Plate_1avg=(268.8+268.5+269.7+272.8+266.4+266.3+273.3+271.1+272.8)/9

Q_1act=(C_1*60*(((2*32.17*(Plate_1avg/47.88))/(.0827))^.5)*3.1416*1.5^2)+(C_2*60
*(((2*32.17*(Plate_1avg/47.88))/(.0827))^.5)*3.1416*1.58^2)

Q_1pred=C*((P_11^n)+(P_12^n)+(P_13^n)+(P_14^n)+(P_15^n))

Error_1=((Q_1act-Q_1pred)^2)^.5

"Test 2 - 28 May 1997"
P_21=37.5
P_22=39
P_23=40.5
P_24=41
P_25=42

Plate_2avg=(270+272.6+270.6+274.4+266.6+273.3+273.4+276.6+271)/9

Q_2act=(C_1*60*(((2*32.17*(Plate_2avg/47.88))/(.0827))^.5)*3.1416*1.5^2)+(C_2*60
*(((2*32.17*(Plate_2avg/47.88))/(.0827))^.5)*3.1416*1.58^2)

Q_2pred=C*((P_21^n)+(P_22^n)+(P_23^n)+(P_24^n)+(P_25^n))

Error_2=((Q_2act-Q_2pred)^2)^.5

"Test 3 - 28 May 1997"
P_31=23
P_32=24.5
P_33=27
P_34=27.5
```

```
P_35=29

Q_3act=34732

Q_3pred=C*((P_31^n)+(P_32^n)+(P_33^n)+(P_34^n)+(P_35^n))

Error_3=((Q_3act-Q_3pred)^2)^.5

"Test 4 - 28 May 1997"
P_41=18.5
P_42=19.5
P_43=21.5
P_44=23
P_45=24

Q_4act=25420

Q_4pred=C*((P_41^n)+(P_42^n)+(P_43^n)+(P_44^n)+(P_45^n))

Error_4=((Q_4act-Q_4pred)^2)^.5

"Test 5 - 28 May 1997"
P_51=12.5
P_52=15
P_53=16.5
P_54=17.5
P_55=20

Q_5act=20132

Q_5pred=C*((P_51^n)+(P_52^n)+(P_53^n)+(P_54^n)+(P_55^n))

Error_5=((Q_5act-Q_5pred)^2)^.5

"Test 6 - 28 May 1997"
P_61=10.5
P_62=12
P_63=14
P_64=15.5
P_65=18

Q_6act=16965

Q_6pred=C*((P_61^n)+(P_62^n)+(P_63^n)+(P_64^n)+(P_65^n))

Error_6=((Q_6act-Q_6pred)^2)^.5
```

"Total Error"
Error_Tot=(Error_1^2+Error_2^2+Error_3^2+Error_4^2+Error_5^2+Error_6^2)^0.5

B1.2.2b Solving for C and n - Solutions (28 May)

n	C	Total Error
0.40	1500.0	48226
0.42	1500.0	45590
0.44	1500.0	42702
0.46	1500.0	39541
0.48	1449.9	37226
0.50	1358.3	35896
0.52	1272.4	34569
0.54	1191.9	33245
0.56	1116.6	31923
0.58	1045.9	30604
0.60	979.8	29288
0.62	917.8	27973
0.64	859.8	26661
0.66	805.4	25351
0.68	754.5	24043
0.70	706.7	22737
0.72	662.0	21433
0.74	620.2	20130
0.76	580.9	18828
0.78	544.2	17528
0.80	509.8	16229
0.82	477.5	14931
0.84	443.6	14097
0.86	412.1	13295
0.88	382.8	12511
0.90	355.5	11744
0.92	330.3	10995
0.94	306.8	10263
0.96	284.9	9547
0.98	264.7	8848
1.00	247.0	8339
1.02	233.5	8304
1.04	220.8	8274
1.06	208.8	8246
1.08	197.4	8222
1.10	186.6	8201
1.12	176.4	8183
1.14	164.7	8687
1.16	153.3	9351
1.18	142.7	10007

n	C	Total Error
1.20	132.8	10653
1.22	123.6	11291
1.24	115.1	11921
1.26	107.1	12763
1.28	99.7	13900
1.30	92.8	15023
1.32	86.4	16133
1.34	80.4	17230
1.36	74.8	18317
1.38	70.0	19494
1.40	64.8	20444
1.42	60.4	21491
1.44	56.2	22526
1.46	52.3	23549
1.48	48.7	24559
1.50	45.3	25558
1.52	42.2	26547
1.54	39.2	27523
1.56	36.5	28489
1.58	34.0	29444
1.60	31.6	30389
1.62	29.5	31323
1.64	27.4	32246
1.66	25.5	33160
1.68	23.8	34063
1.70	22.1	34957
1.72	20.6	35841
1.74	19.2	36715
1.76	17.8	37580
1.78	16.6	38436
1.80	15.4	39282
1.82	14.4	40119
1.84	13.4	40948
1.86	12.5	41768
1.88	11.6	42579
1.90	10.8	43382
1.92	10.0	44177
1.94	9.3	44963
1.96	8.7	45741
1.98	8.1	46512

Table A2 - Determining C and n by Minimizing Total Error (28 May 1997)

B1.2.3a Solving for C and n - Equations (29 May)

```
"Error Analysis -     Test Date:  29 May 1997"

"Discharge Coefficients were determined using the 29Flow.ees program and are used to
find the actual flow in Tests 1 and 2"
C_1=0.847
C_2=0.866

"Test 1 - 29 May 1997
No Flow Measurements - Velocity was too high across the plate to "
P_11=34.5
P_12=36
P_13=36.5
P_14=37
P_15=37.5

Plate_1avg=(258.4+260+263.2+258.9+263.1+263.1+262.2+263.6+261.4)/9

Q_1act=(C_1*60*(((2*32.17*(Plate_1avg/47.88))/(.0827))^.5)*3.1416*1.5^2)+(C_2*60
*(((2*32.17*(Plate_1avg/47.88))/(.0827))^.5)*3.1416*1.58^2)

Q_1pred=C*((P_11^n)+(P_12^n)+(P_13^n)+(P_14^n)+(P_15^n))

Error_1=((Q_1act-Q_1pred)^2)^.5

"Test 2 - 29 May 1997"
P_21=34.5
P_22=25.5
P_23=25.5
P_24=27
P_25=28

Plate_2avg=(200.2+201.5+197.1+196.5+196+196.6+193+198+196.6+196.9)/10

Q_2act=(C_1*60*(((2*32.17*(Plate_2avg/47.88))/(.0827))^.5)*3.1416*1.5^2)+(C_2*60
*(((2*32.17*(Plate_2avg/47.88))/(.0827))^.5)*3.1416*1.58^2)
Q_2pred=C*((P_21^n)+(P_22^n)+(P_23^n)+(P_24^n)+(P_25^n))

Error_2=((Q_2act-Q_2pred)^2)^.5

"Test 3 - 29 May 1997"
P_31=24
P_32=24.5
P_33=25
P_34=25.5
P_35=25.5
```

```
Q_3act=32409
Q_3pred=C*((P_31^n)+(P_32^n)+(P_33^n)+(P_34^n)+(P_35^n))

Error_3=((Q_3act-Q_3pred)^2)^.5

"Test 4 - 29 May 1997"
P_41=19.5
P_42=20.5
P_43=20.5
P_44=21
P_45=21

Q_4act=28834
Q_4pred=C*((P_41^n)+(P_42^n)+(P_43^n)+(P_44^n)+(P_45^n))

Error_4=((Q_4act-Q_4pred)^2)^.5

"Test 5 - 29 May 1997"
P_51=15.5
P_52=16
P_53=17.5
P_54=19.5
P_55=19.5

Q_5act=23971
Q_5pred=C*((P_51^n)+(P_52^n)+(P_53^n)+(P_54^n)+(P_55^n))

Error_5=((Q_5act-Q_5pred)^2)^.5

"Test 6 - 29 May 1997"
P_61=7.7
P_62=8.5
P_63=9.5
P_64=10.5
P_65=13.5

Q_6act=14665

Q_6pred=C*((P_61^n)+(P_62^n)+(P_63^n)+(P_64^n)+(P_65^n))

Error_6=((Q_6act-Q_6pred)^2)^.5

"Total Error"

Error_Tot=Error_1+Error_2+Error_3+Error_4+Error_5+Error_6
```

B1.2.3b Solving for C and n - Solutions (29 May)

n	C	Total Error
0.40	1500.0	46831
0.42	1500.0	40670
0.44	1500.0	34861
0.46	1477.3	31543
0.48	1385.3	30477
0.50	1299.1	29418
0.52	1218.2	28366
0.54	1142.3	27320
0.56	1071.2	26280
0.58	1004.5	25246
0.60	941.9	24217
0.62	886.5	23304
0.64	834.5	22395
0.66	785.6	21484
0.68	739.6	20570
0.70	696.2	19654
0.72	655.4	18736
0.74	617.0	17814
0.76	580.8	16890
0.78	546.8	15963
0.80	514.7	15032
0.82	484.5	14098
0.84	456.1	13161
0.86	429.4	12220
0.88	404.2	11276
0.90	380.5	10327
0.92	358.2	9375
0.94	339.0	8500
0.96	317.9	8002
0.98	295.9	8178
1.00	275.4	8439
1.02	257.2	8791
1.04	245.0	9706
1.06	229.3	10120
1.08	216.5	10794
1.10	204.4	11475
1.12	193.0	12163
1.14	182.2	12858
1.16	172.0	13560
1.18	163.2	14430

n	C	Total Error
1.20	153.3	14985
1.22	144.7	15715
1.24	136.2	16479
1.26	128.3	17249
1.28	120.7	18023
1.30	113.3	18834
1.32	105.9	19670
1.34	99.1	20499
1.36	92.7	21322
1.38	86.7	22139
1.40	81.0	22949
1.42	75.8	23753
1.44	70.9	24552
1.46	66.3	25344
1.48	62.0	26131
1.50	58.0	26911
1.52	54.2	27687
1.54	50.7	28457
1.56	43.0	29153
1.58	40.3	29851
1.60	37.8	30536
1.62	35.5	31226
1.64	33.3	31916
1.66	31.2	32605
1.68	29.2	33293
1.70	27.4	33981
1.72	25.7	34668
1.74	24.1	35355
1.76	22.6	36042
1.78	21.2	36728
1.80	19.9	37414
1.82	18.6	38100
1.84	17.5	38787
1.86	16.4	39471
1.88	15.4	40158
1.90	14.4	40844
1.92	13.5	41530
1.94	12.7	42217
1.96	11.9	42904
1.98	11.1	43631

Table B3 - Determining C and n by Minimizing Total Error (29 May 1997)

Appendix C

Tracer Gas Results and Analysis for Pattee East Library

Appendix C

Tracer Gas Result and Analysis for Pattee East Library

C1.1 Automatic Tracer Gas Monitor Analysis

The tracer gas monitor measures and writes all the information about a series of tests to a disk to ensure that data is correctly recorded during the test. The critical information on the printout is the time and the concentration. The test operator must record the time when the tracer gas is turned on, and the flow rate. From this information, and the knowledge of the gas concentration in the canister, the flow rate through the fan can be calculated using Equation 4.7. This is explained in great detail in Section 6.2. The concentration, time and flow rates are displayed below for each test on a given day. The graphs represent display the concentration vs. time for each test. Each test was repeated with the same conditions to determine the repeatability of the procedure.

C1.1 Automatic Tracer Gas Monitor Results - (9 July 1997)

Time (min)	*Concentration (ppb)*	*Airflow Rate*
2	0.021	2537439
4	0.34	156724.174
6	0.809	65866.7727
8	0.789	67536.3993
10	0.85	62689.6695
12	0.872	61108.0494
2	0.118	451578.128
4	0.562	94815.3364
6	0.891	59804.9597
8	0.902	59075.6309
10	0.91	58556.2847
12	0.909	58620.7031

Table C1
Tracer Gas Results

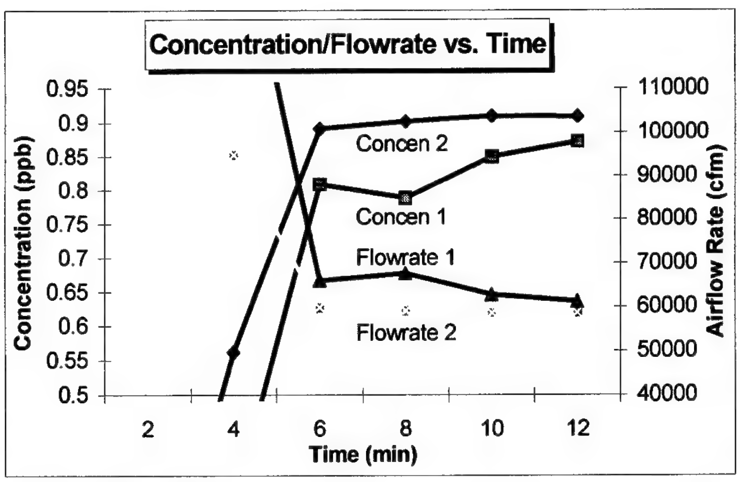


Figure C1 - Concentration/Flowrate vs. Time
(Test 1)

Time (min)	Concentration (ppb)	Airflow Rate
2	0.109	488864.395
4	0.764	69746.3601
6	0.954	55855.5756
8	0.996	53500.22
10	0.996	53500.22
12	1.03	51734.1933
2	0.135	394712.734
4	0.857	62177.6185
6	0.937	56868.9638
8	1.02	52241.3913
10	1.01	52758.6328
12	1.01	52758.6328

Table C2
Tracer Gas Results

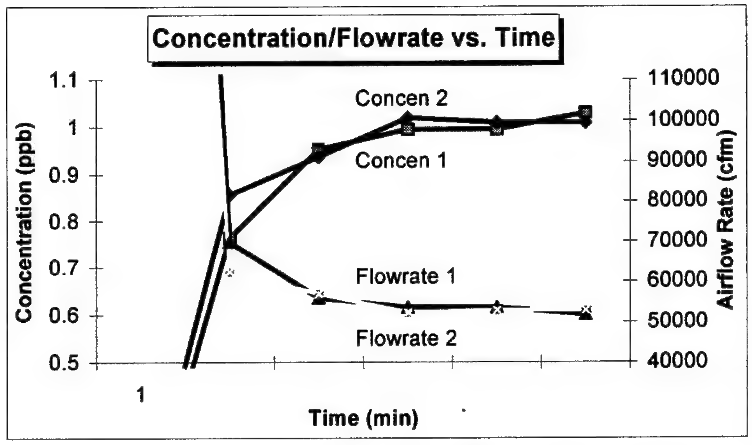


Figure C2 - Concentration/Flowrate vs. Time
(Test 2)

Time (min)	Concentration (ppb)	Airflow Rate
2	0.195	273262.662
4	0.936	56929.7212
6	1.15	46335.8427
8	1.21	44038.1976
10	1.2	44405.1826
12	1.15	46335.8427
2	0.258	206535.733
4	1.06	50270.018
6	1.25	42628.9753
8	1.28	41629.8587
10	1.26	42290.6501
12	1.26	42290.6501

Table C3
Tracer Gas Results

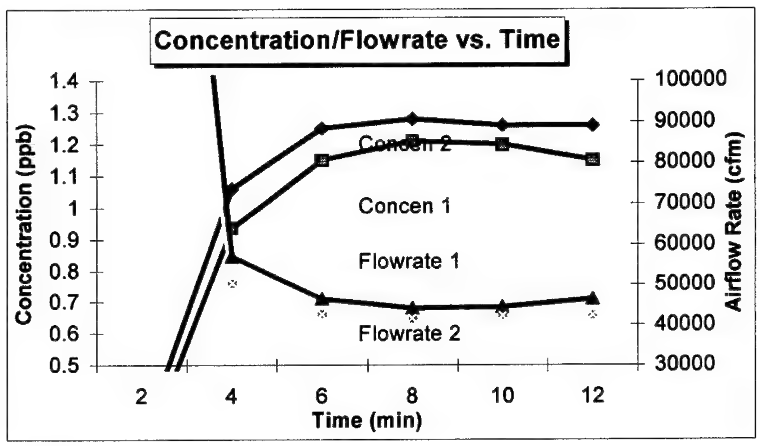


Figure C3 - Concentration/Flowrate vs. Time
(Test 3)

Time (min)	Concentration (ppb)	Airflow Rate
2	0.31	171891.029
4	0.945	56387.5334
6	1.35	39471.2734
8	1.33	40064.8264
10	1.39	38335.4094
12	1.39	38335.4094
2	0.535	99600.4095
4	0.952	55972.9192
6	1.36	39181.0434
8	1.37	38895.0504
10	1.39	38335.4094
12	1.38	38613.2022

Table C4
Tracer Gas Results

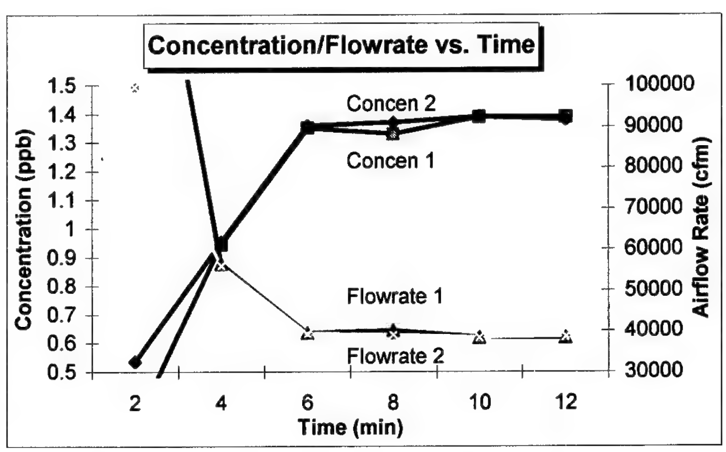


Figure C4 - Concentration/Flowrate vs. Time
(Test 4)

B1.2 Automatic Tracer Gas Monitor Results - (10 July 1997)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.006	8881037
4	0.513	103872
6	0.811	65704
8	0.858	62105
10	0.883	60347
12	0.912	58428
14	0.954	55856
2	0.177	301052
4	0.842	63285
6	0.956	55739
8	0.961	55449
10	1	53286
12	1.05	50749
14	1.01	52759

Table C5
Tracer Gas Results

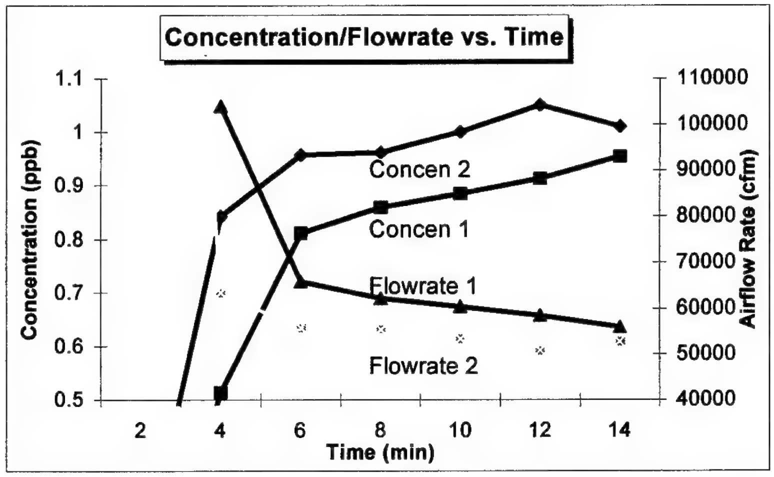


Figure C5 - Concentration/Flowrate vs. Time
(Test 1)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.217	245559
4	0.959	55564
6	1.06	50270
8	1.08	49339
10	1.1	48442
12	1.07	49800
14	1.08	49339
2	0.441	120830
4	0.711	74945
6	1.07	49800
8	1.06	50270
10	1.07	49800
12	1.08	49339
14	1.08	49339

Table C6
Tracer Gas Results

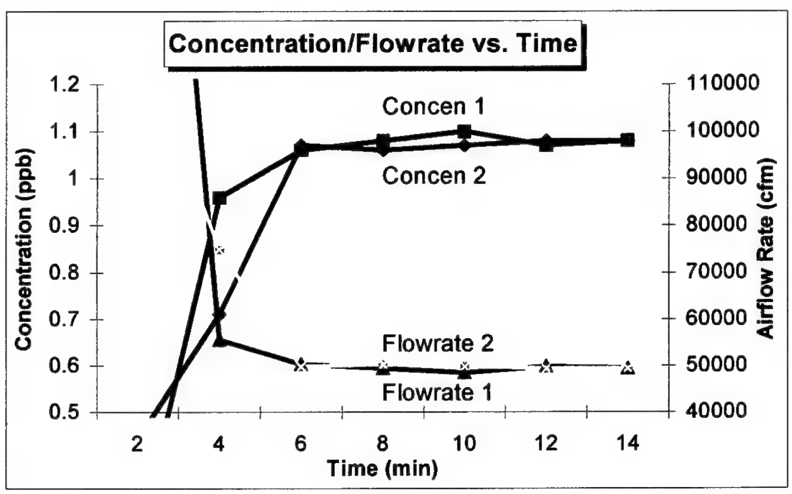


Figure C6 - Concentration/Flowrate vs. Time
(Test 2)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.201	265106
4	0.203	262494
6	1.06	50270
8	1.11	48006
10	1.11	48006
12	1.14	46742
14	1.14	46742
2	0.208	256184
4	1.04	51237
6	1.09	48886
8	1.13	47156
10	1.15	46336
12	1.15	46336
14	1.13	47156

Table C7
Tracer Gas Results

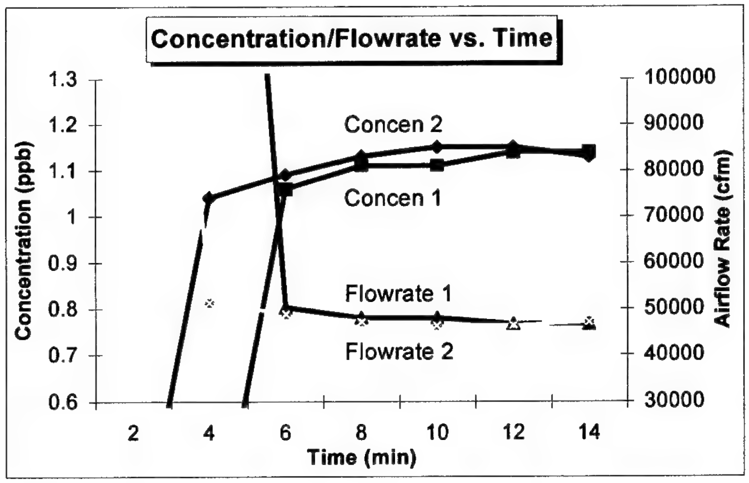


Figure C7 - Concentration/Flowrate vs. Time
(Test 3)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.269	198090
4	0.725	73498
6	1.21	44038
8	1.23	43322
10	1.21	44038
12	1.21	44038
14	1.24	42973
2	0.271	196628
4	0.277	192369
6	1.23	43322
8	1.23	43322
10	1.27	41958
12	1.3	40989
14	1.29	41307

Table C8
Tracer Gas Results

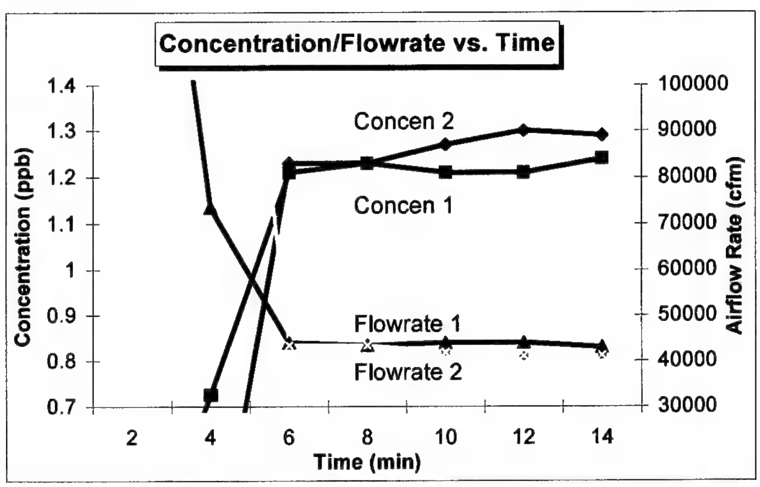


Figure C8 - Concentration/Flowrate vs. Time
(Test 4)

B1.3 Automatic Tracer Gas Monitor Results - (16 July 1997)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.166	321001
4	0.773	68934
6	1.06	50270
8	1.06	50270
10	1.04	51237
12	1.1	48442
14	1.1	48442
2	0.449	118678
4	0.961	55449
6	1.1	48442
8	1.14	46742
10	1.16	45936
12	1.17	45544
14	1.19	44778

Table C9
Tracer Gas Results

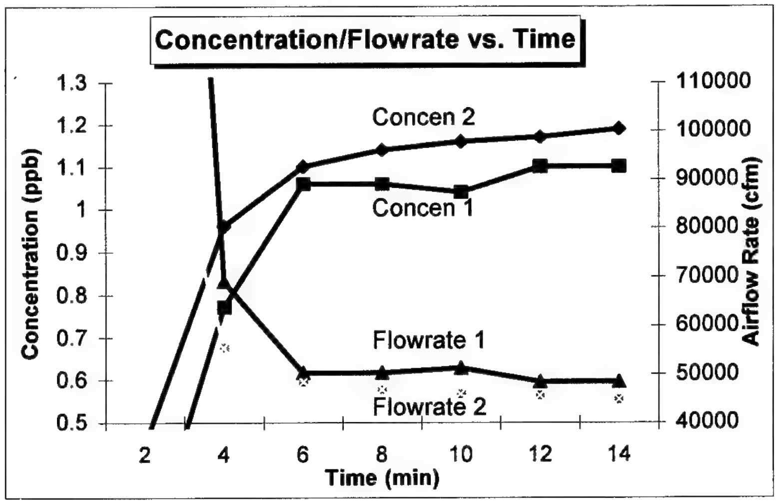


Figure C9 - Concentration/Flowrate vs. Time
(Test 1)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.299	178215
4	0.83	64200
6	1.17	45544
8	1.16	45936
10	1.17	45544
12	1.16	45936
14	1.14	46742
2	0.345	154453
4	0.933	57113
6	1.2	44405
8	1.17	45544
10	1.18	45158
12	1.2	44405
14	1.19	44778

Table C10
Tracer Gas Results

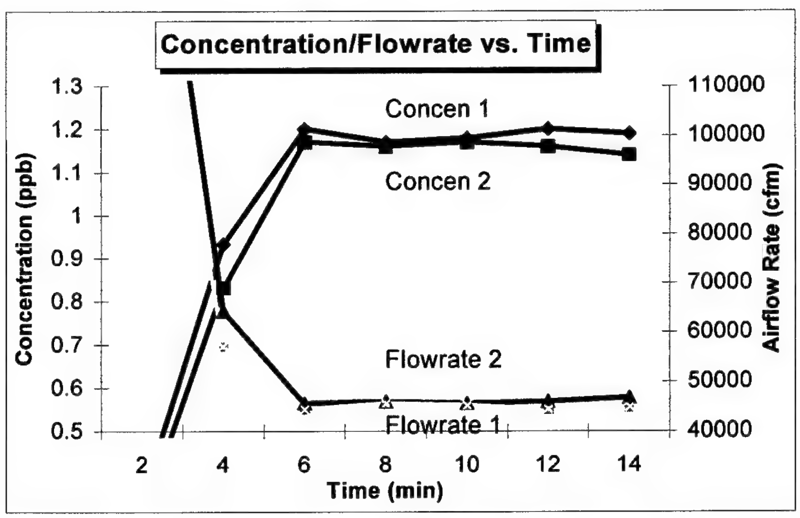


Figure C10 - Concentration/Flowrate vs. Time
(Test 2)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.218	244432
4	0.637	83652
6	1.09	48886
8	1.14	46742
10	1.14	46742
12	1.14	46742
14	1.16	45936
2	0.256	208149
4	0.274	194475
6	1.02	52241
8	1.19	44778
10	1.2	44405
12	1.16	45936
14	1.24	42973

Table C11
Tracer Gas Results

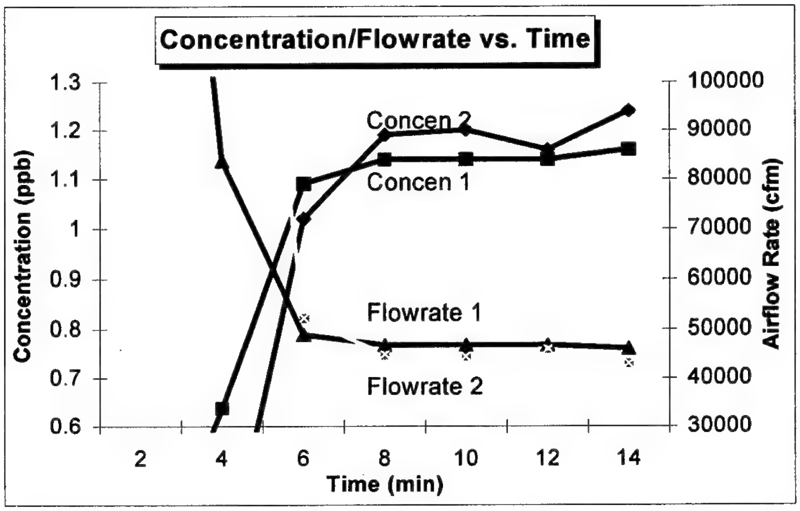


Figure C11 - Concentration/Flowrate vs. Time
(Test 3)

Time (min)	Concen (ppb)	Flow Rate (cfm)
2	0.336	158590
4	0.314	169701
6	1.26	42291
8	1.36	39181
10	1.37	38895
12	1.4	38062
14	1.38	38613
2	0.468	113859
4	0.887	60075
6	1.39	38335
8	1.44	37004
10	1.44	37004
12	1.44	37004
14	1.48	36004

Table C12
Tracer Gas Results

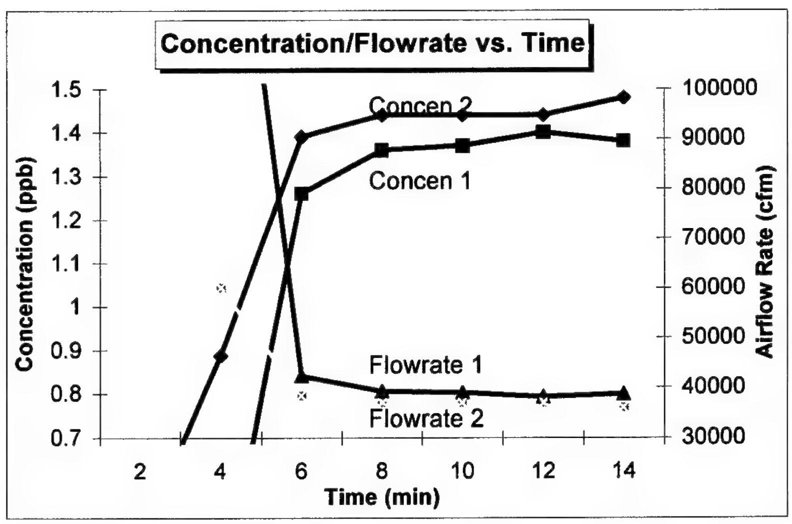


Figure C12 - Concentration/Flowrate vs. Time
(Test 4)

C1.2 Solving the Power Law Equation by Minimizing RMS Error

The set of equations listed below is titled "Error Analysis," but this actually refers to minimizing the root mean square error produce by selecting the best fit C value for a given range of "n" values. This is explained in full detail in Section 6.2. The differential pressure measurements across the building floors are averaged and input into the P_xy variable. The x indicates the test run and the y is the floor corresponding to the recorded pressure. The actual outdoor air flow was determined in the orifice plate calibration and is designated Q_xact. The predicted airflow, Q_xpred, is the value which is being set equal to the actual airflow. Q_xpred is based on Equation 13 and uses the average pressure previously described. The solution is set to minimize the total error, Error_tot, for a given n value, by selecting C. The solutions to the test runs for each day follow the equation list.

C1.2.1a Solving for C and n - Equations (9 July)

```
"Error Analysis -      Test Date: 9 July 1997"

"Test 1 - 9 July 1997"
P_11=10.7
P_12=11.6
P_13=11.2
P_14=16.6
P_15=11

Q_1act=63778

Q_1pred=C*((P_11^n)+(P_12^n)+(P_13^n)+(P_14^n)+(P_15^n))

Error_1=((Q_1act-Q_1pred)^2)

"Test 2 - 9 July 1997"
P_21=10.3
P_22=14.4
P_23=11.6
P_24=13.9
P_25=12.5

Q_2act=58751

Q_2pred=C*((P_21^n)+(P_22^n)+(P_23^n)+(P_24^n)+(P_25^n))

Error_2=((Q_2act-Q_2pred)^2)

"Test 3 - 9 July 1997"
P_31=8.1
P_32=8.4
```

```
P_33=9.6
P_34=11.4
P_35=10.5

Q_3act=52912

Q_3pred=C*((P_31^n)+(P_32^n)+(P_33^n)+(P_34^n)+(P_35^n))

Error_3=((Q_3act-Q_3pred)^2)

"Test 4 - 9 July 1997"
P_41=7.2
P_42=9.6
P_43=9.6
P_44=11.4
P_45=10.4

Q_4act=52586

Q_4pred=C*((P_41^n)+(P_42^n)+(P_43^n)+(P_44^n)+(P_45^n))

Error_4=((Q_4act-Q_4pred)^2)

"Test 5 - 9 July 1997"
P_51=5.7
P_52=5.8
P_53=7.7
P_54=8.9
P_55=7.8

Q_5act=44926

Q_5pred=C*((P_51^n)+(P_52^n)+(P_53^n)+(P_54^n)+(P_55^n))

Error_5=((Q_5act-Q_5pred)^2)

"Test 6 - 9 July 1997"
P_61=5.2
P_62=6.2
P_63=6.6
P_64=8.3
P_65=8.2

Q_6act=42070

Q_6pred=C*((P_61^n)+(P_62^n)+(P_63^n)+(P_64^n)+(P_65^n))
```

```
Error_6=((Q_6act-Q_6pred)^2)

"Test 7 - 9 July 1997"
P_71=3.4
P_72=4.5
P_73=4.5
P_74=6.6
P_75=5.9

Q_7act=38912

Q_7pred=C*((P_71^n)+(P_72^n)+(P_73^n)+(P_74^n)+(P_75^n))

Error_7=((Q_7act-Q_7pred)^2)

"Test 8 - 9 July 1997"
P_81=1.6
P_82=2.3
P_83=4.1
P_84=5.9
P_85=6

Q_8act=38615

Q_8pred=C*((P_81^n)+(P_82^n)+(P_83^n)+(P_84^n)+(P_85^n))

Error_8=((Q_8act-Q_8pred)^2)

"Total Error"

RMSErr_Tot=((Error_1+Error_2+Error_3+Error_4+Error_5+Error_6+Error_7+Error_8)/
8)^.5
```

C1.2.1b Solving for C and n - Solutions (9 July)

n	C	Total Error
0.40	4296.1	2782
0.42	4114.3	2678
0.44	3939.5	2616
0.46	3771.5	2596
0.48	3610.1	2620
0.50	3455.1	2684
0.52	3306.3	2785
0.54	3163.4	2918
0.56	3026.2	3079
0.58	2894.6	3261
0.60	2768.3	3462
0.62	2647.2	3677
0.64	2531.0	3904
0.66	2419.7	4139
0.68	2312.9	4382
0.70	2210.5	4630
0.72	2112.4	4881
0.74	2018.4	5136
0.76	1928.4	5393
0.78	1842.2	5651
0.80	1759.6	5910
0.82	1680.5	6170
0.84	1604.8	6429
0.86	1532.4	6688
0.88	1463.0	6947
0.90	1396.7	7205
0.92	1333.2	7462
0.94	1272.5	7718
0.96	1214.4	7972
0.98	1158.9	8225
1.00	1105.8	8477
1.02	1055.0	8727
1.04	1006.5	8976
1.06	960.1	9223
1.08	915.7	9468
1.10	873.4	9711
1.12	832.9	9953
1.14	794.2	10193
1.16	757.3	10431
1.18	722.0	10667

n	C	Total Error
1.20	688.3	10901
1.22	656.1	11133
1.24	625.4	11364
1.26	596.1	11592
1.28	568.1	11819
1.30	541.4	12044
1.32	515.9	12266
1.34	491.6	12487
1.36	468.3	12706
1.38	446.2	12923
1.40	425.1	13139
1.42	404.9	13352
1.44	385.7	13564
1.46	367.3	13773
1.48	349.8	13981
1.50	333.2	14187
1.52	317.2	14391
1.54	302.1	14593
1.56	287.6	14794
1.58	273.9	14993
1.60	260.7	15189
1.62	248.2	15385
1.64	236.3	15578
1.66	224.9	15770
1.68	214.1	15959
1.70	203.7	16148
1.72	193.9	16334
1.74	184.5	16519
1.76	175.6	16702
1.78	167.1	16883
1.80	159.0	17063
1.82	151.3	17241
1.84	143.9	17418
1.86	137.0	17593
1.88	130.3	17766
1.90	123.9	17938
1.92	117.9	18108
1.94	112.2	18276
1.96	106.7	18443
1.98	101.5	18609

Table C13 - Determining C and n by Minimizing Total Error (9 July 1997)

C1.2.2a Solving for C and n - Equations (10 July)

```
"Error Analysis -      Test Date:  10 July 1997"

"Test 1 - 10 July 1997"
P_11=11.3
P_12=11.3
P_13=11.6
P_14=12.6
P_15=10.6

Q_1act=58210

Q_1pred=C*((P_11^n)+(P_12^n)+(P_13^n)+(P_14^n)+(P_15^n))

Error_1=(Q_1act-Q_1pred)^2

"Test 2 - 10 July 1997"
P_21=10.2
P_22=11.2
P_23=12.3
P_24=12.4
P_25=12

Q_2act=52267

Q_2pred=C*((P_21^n)+(P_22^n)+(P_23^n)+(P_24^n)+(P_25^n))

Error_2=(Q_2act-Q_2pred)^2

"Test 3 - 10 July 1997"
P_31=8.1
P_32=8.7
P_33=9.6
P_34=10.4
P_35=10.7

Q_3act=49194

Q_3pred=C*((P_31^n)+(P_32^n)+(P_33^n)+(P_34^n)+(P_35^n))

Error_3=(Q_3act-Q_3pred)^2

"Test 4 - 10 July 1997"
P_41=8.5
P_42=9.1
P_43=10.1
```

```
P_44=10.9
P_45=10.1

Q_4act=49493

Q_4pred=C*((P_41^n)+(P_42^n)+(P_43^n)+(P_44^n)+(P_45^n))

Error_4=((Q_4act-Q_4pred)^2)

"Test 5 - 10 July 1997"
P_51=7
P_52=9
P_53=9.4
P_54=10.5
P_55=10.7

Q_5act=47163

Q_5pred=C*((P_51^n)+(P_52^n)+(P_53^n)+(P_54^n)+(P_55^n))

Error_5=((Q_5act-Q_5pred)^2)

"Test 6 - 10 July 1997"
P_61=7.4
P_62=8.5
P_63=9.4
P_64=10
P_65=10

Q_6act=46609

Q_6pred=C*((P_61^n)+(P_62^n)+(P_63^n)+(P_64^n)+(P_65^n))

Error_6=((Q_6act-Q_6pred)^2)

"Test 7 - 10 July 1997"
P_71=5.6
P_72=5.8
P_73=6.5
P_74=7.5
P_75=7.9

Q_7act=43683

Q_7pred=C*((P_71^n)+(P_72^n)+(P_73^n)+(P_74^n)+(P_75^n))
```

```
Error_7=((Q_7act-Q_7pred)^2)

"Test 8 - 10 July 1997"
P_81=4.9
P_82=5.3
P_83=6.3
P_84=7.2
P_85=8

Q_8act=41418

Q_8pred=C*((P_81^n)+(P_82^n)+(P_83^n)+(P_84^n)+(P_85^n))

Error_8=((Q_8act-Q_8pred)^2)

"Total Error"

RMSErr_Tot=((Error_1+Error_2+Error_3+Error_4+Error_5+Error_6+Error_7+Error_8)/
8)^.5
```

C1.2.2b Solving for C and n - Solutions (10 July)

n	C	Total Error
0.40	4019.4	2042
0.42	3844.0	2007
0.44	3676.0	1989
0.46	3515.2	1990
0.48	3361.2	2009
0.50	3213.9	2044
0.52	3072.8	2096
0.54	2937.8	2162
0.56	2808.6	2242
0.58	2684.9	2333
0.60	2566.6	2434
0.62	2453.3	2544
0.64	2345.0	2661
0.66	2241.3	2785
0.68	2142.1	2915
0.70	2047.2	3049
0.72	1956.4	3186
0.74	1869.6	3327
0.76	1786.5	3471
0.78	1707.1	3617
0.80	1631.1	3765
0.82	1558.4	3915
0.84	1488.9	4066
0.86	1422.4	4217
0.88	1358.9	4370
0.90	1298.1	4523
0.92	1240.0	4677
0.94	1184.5	4831
0.96	1131.4	4986
0.98	1080.6	5140
1.00	1032.1	5295
1.02	985.7	5449
1.04	941.4	5604
1.06	899.0	5758
1.08	858.5	5912
1.10	819.8	6066
1.12	782.8	6219
1.14	747.4	6372
1.16	713.7	6525
1.18	681.4	6677

n	C	Total Error
1.20	650.5	6829
1.22	621.1	6980
1.24	592.9	7131
1.26	566.0	7281
1.28	540.3	7431
1.30	515.8	7580
1.32	492.3	7728
1.34	470.0	7876
1.36	448.6	8023
1.38	428.1	8170
1.40	408.6	8316
1.42	390.0	8461
1.44	372.2	8606
1.46	355.2	8750
1.48	339.0	8893
1.50	323.5	9036
1.52	308.7	9178
1.54	294.5	9319
1.56	281.0	9460
1.58	268.1	9600
1.60	255.8	9739
1.62	244.1	9878
1.64	232.9	10016
1.66	222.2	10153
1.68	212.0	10289
1.70	202.2	10425
1.72	192.9	10560
1.74	184.0	10695
1.76	175.6	10828
1.78	167.5	10961
1.80	159.7	11094
1.82	152.4	11225
1.84	145.3	11356
1.86	138.6	11487
1.88	132.2	11616
1.90	126.1	11745
1.92	120.3	11873
1.94	114.7	12001
1.96	109.4	12127
1.98	104.3	12254

Table C14 - Determining C and n by Minimizing Total Error (10 July 1997)

C1.2.3a Solving for C and n - Equations (16 July)

"Error Analysis - Test Date: 22 May 1997"

"Test 1 - 10 July 1997"
P_11=9.2
P_12=9.0
P_13=10
P_14=8.2
P_15=9.2

Q_1act=49374

Q_1pred=C*((P_11^n)+(P_12^n)+(P_13^n)+(P_14^n)+(P_15^n))

Error_1=(Q_1act-Q_1pred)^2

"Test 2 - 10 July 1997"
P_21=8.5
P_22=8.6
P_23=8.9
P_24=8.5
P_25=8.5

Q_2act=45420

Q_2pred=C*((P_21^n)+(P_22^n)+(P_23^n)+(P_24^n)+(P_25^n))

Error_2=(Q_2act-Q_2pred)^2

"Test 3 - 10 July 1997"
P_31=8.2
P_32=7.6
P_33=7.9
P_34=7.8
P_35=7.7

Q_3act=46074

Q_3pred=C*((P_31^n)+(P_32^n)+(P_33^n)+(P_34^n)+(P_35^n))

Error_3=(Q_3act-Q_3pred)^2
"Test 4 - 10 July 1997"
P_41=7.5
P_42=7.4
P_43=7.8
P_44=6.7

```
P_45=7.6

Q_4act=44780

Q_4pred=C*((P_41^n)+(P_42^n)+(P_43^n)+(P_44^n)+(P_45^n))

Error_4=((Q_4act-Q_4pred)^2)

"Test 5 - 10 July 1997"
P_51=6.9
P_52=6.7
P_53=7.1
P_54=6.8
P_55=7.3

Q_5act=46474

Q_5pred=C*((P_51^n)+(P_52^n)+(P_53^n)+(P_54^n)+(P_55^n))

Error_5=((Q_5act-Q_5pred)^2)

"Test 6 - 10 July 1997"
P_61=7.7
P_62=7.9
P_63=8.2
P_64=8.1
P_65=8.3

Q_6act=44438

Q_6pred=C*((P_61^n)+(P_62^n)+(P_63^n)+(P_64^n)+(P_65^n))

Error_6=((Q_6act-Q_6pred)^2)

"Test 7 - 10 July 1997"
P_71=5
P_72=5.4
P_73=5.2
P_74=5.4
P_75=5.6

Q_7act=38523

Q_7pred=C*((P_71^n)+(P_72^n)+(P_73^n)+(P_74^n)+(P_75^n))

Error_7=((Q_7act-Q_7pred)^2)
```

```
"Test 8 - 10 July 1997"
P_81=5
P_82=4.8
P_83=4.8
P_84=5
P_85=4.9

Q_8act=36671

Q_8pred=C*((P_81^n)+(P_82^n)+(P_83^n)+(P_84^n)+(P_85^n))

Error_8=((Q_8act-Q_8pred)^2)

"Total Error"

RMSErr_Tot=((Error_1+Error_2+Error_3+Error_4+Error_5+Error_6+Error_7+Error_8)/
8)^.5
```

C1.2.3b Solving for C and n - Solutions (16 July)

n	C	Total Error
0.40	3997.4	1496
0.42	3840.9	1494
0.44	3690.4	1512
0.46	3545.6	1548
0.48	3406.3	1602
0.50	3272.4	1671
0.52	3143.6	1753
0.54	3019.7	1847
0.56	2900.6	1950
0.58	2786.1	2061
0.60	2676.0	2179
0.62	2570.1	2302
0.64	2468.3	2430
0.66	2370.4	2561
0.68	2276.4	2695
0.70	2185.9	2832
0.72	2099.0	2970
0.74	2015.5	3110
0.76	1935.2	3252
0.78	1858.0	3394
0.80	1783.9	3537
0.82	1712.6	3681
0.84	1644.1	3825
0.86	1578.3	3970
0.88	1515.1	4114
0.90	1454.4	4259
0.92	1396.0	4403
0.94	1339.9	4548
0.96	1286.1	4692
0.98	1234.3	4836
1.00	1184.7	4980
1.02	1136.9	5124
1.04	1091.1	5267
1.06	1047.0	5409
1.08	1004.8	5552
1.10	964.1	5694
1.12	925.1	5835
1.14	887.7	5976
1.16	851.7	6116
1.18	817.2	6256

n	C	Total Error
1.20	784.0	6395
1.22	752.2	6534
1.24	721.6	6672
1.26	692.3	6809
1.28	664.1	6946
1.30	637.1	7082
1.32	611.1	7218
1.34	586.2	7353
1.36	562.3	7487
1.38	539.4	7621
1.40	517.3	7754
1.42	496.2	7886
1.44	475.9	8018
1.46	456.4	8149
1.48	437.7	8280
1.50	419.8	8409
1.52	402.6	8538
1.54	386.1	8667
1.56	370.2	8794
1.58	355.0	8922
1.60	340.4	9048
1.62	326.4	9174
1.64	313.0	9299
1.66	300.1	9423
1.68	287.7	9547
1.70	275.9	9670
1.72	264.5	9792
1.74	253.6	9914
1.76	243.1	10035
1.78	233.1	10155
1.80	223.5	10275
1.82	214.2	10394
1.84	205.4	10512
1.86	196.9	10630
1.88	188.7	10747
1.90	180.9	10863
1.92	173.4	10979
1.94	166.2	11094
1.96	159.3	11208
1.98	152.7	11322

Table C15 - Determining C and n by Minimizing Total Error (16 July 1997)

Appendix D

Tracer Gas Results and Analysis for the USX Tower

Appendix D

Tracer Gas Result and Analysis for the USX Tower

D1.1 Automatic Tracer Gas Monitor Analysis

The tracer gas monitor measures and automatically saves all the information about a series of tests to disk to ensure that all data is correctly recorded during the test. The critical information on the printout is the time and the concentration level. The test operator must record the time when the tracer gas is turned on, and the flow rate. From this information, and the knowledge of the gas concentration in the canister, the flow rate through the fan can be calculated using Equation 4.7. This is explained in great detail in Section 6.2. The concentration, time and flow rates are displayed below for each test on a given day. The results from the USX Tower differ from those in Pattee East Library because two supply fans were used to pressurize the space. The test procedure was completed in the same manner, except the tracer gas monitor alternated testing between the two fans. The shaded regions in the tables below refer to Fan #2. Also, the tracer gas injection lines were routed to the supply grids a bit differently. The gas was sent from the same canister (providing an equal concentration) and it was split to each fan. Measurements were taken on each direction in the split and the total tracer gas flow rate was monitored continuously. The upper tables indicate flow rate to each supply grid.

D1.1 Automatic Tracer Gas Monitor and Su pply Flow Rate Results -(10 August 1997)

Total SF_6 Flow	10
SF_6 to Fan 1 (48%)	4.8
SF_6 to Fan 1 (52%)	5.2

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.025	5088339
4	2	0.029	4752041
6	1	1	127208
8	2	1.26	109372
10	1	1.12	113579
12	2	1.21	113892
14	1	1.18	107804
16	2	1.17	117786
18	1	1.21	105131
20	2	1.2	114841
22	1	1.18	107804
24	2	1.16	118801
26	1	1.21	105131
28	2	1.24	111136

Table 1 - Test 1 Results for Fans 1 & 2

Total SF_6 Flow	10.015
SF_6 to Fan 1 (48%)	4.807
SF_6 to Fan 1 (52%)	5.208

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.025	5088339
4	2	0.009	15312132
6	1	0.945	134612
8	2	0.924	149144
10	1	1.13	112574
12	2	1.12	123044
14	1	1.17	108725
16	2	1.05	131247
18	1	1.14	111586
20	2	1.06	130009
22	1	1.11	114602
24	2	1.1	125281
26	1	1.11	114602
28	2	1.03	133795

Table 2 - Test 2 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	*%*
Fan #1	106467	1543	1.45
Fan #2	115641.021	3441	2.98

Table 3 - Average Flow and Deviation, Test 1

Average Last 4 Measurments			
	Flow	*Std Dev*	*%*
Fan #1	112379	2820	2.51
Fan #2	130082.9798	3568	2.74

Table 4 - Average Flow and Deviation, Test 2

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.082	1551323
4	2	0.054	2552022
6	1	1.14	111586
8	2	1.09	126430
10	1	1.25	101767
12	2	1.1	125281
14	1	1.35	94229
16	2	1.07	128794
18	1	1.32	96370
20	2	1.01	136445
22	1	1.29	98611
24	2	1.05	131247
26	1	1.24	102587
28	2	1.07	128794

Table 5 - Test 3 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	%
Fan #1	97949	3573	3.65
Fan #2	131319.713	3607	2.75

Table 7 - Average Flow and Deviation, Test 4

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.102	1247142
4	2	0.045	3062426
6	1	1.21	105131
8	2	1.05	131247
10	1	1.37	92853
12	2	1.06	130009
14	1	1.25	101767
16	2	1.04	132509
18	1	1.24	102587
20	2	1.05	131247
22	1	1.29	98611
24	2	1.05	131247
26	1	1.24	102587
28	2	1.05	131247

Table 6 - Test 4 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	%
Fan #1	101388	1891	1.87
Fan #2	131562.3423	631	0.48

Table 8 - Average Flow and Deviation, Test 4

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.054	2355713
4	2	0.055	2505622
6	1	1.13	112574
8	2	1.3	106007
10	1	1.47	86536
12	2	1.24	111136
14	1	1.54	82603
16	2	1.22	112958
18	1	1.39	91517
20	2	1.2	114841
22	1	1.54	82603
24	2	1.25	110247
26	1	1.45	87730
28	2	1.1	125281

Table 9 - Test 5 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	%
Fan #1	86113	4338	5.04
Fan #2	115831.942	6576	5.68

Table 11 - Average Flow and Deviation, Test 5

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.067	1898634
4	2	0.07	1968703
6	1	1.32	96370
8	2	1.14	120885
10	1	1.55	82070
12	2	1.17	117786
14	1	1.56	81544
16	2	1.16	118801
18	1	1.49	85375
20	2	1.19	115806
22	1	1.56	81544
24	2	1.16	118801
26	1	1.5	84806
28	2	1.15	119834

Table 10 - Test 5 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	%
Fan #1	83317	2061	2.47
Fan #2	118310.5407	1739	1.47

Table 12 - Average Flow and Deviation, Test 6

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.136	935356
4	2	0.042	3281171
6	1	1.41	90219
8	2	1.37	100591
10	1	1.62	78524
12	2	1.29	106829
14	1	1.63	78042
16	2	1.4	98435
18	1	1.62	78524
20	2	1.35	102081
22	1	1.54	82603
24	2	1.37	100591
26	1	1.4	90863
28	2	1.41	97737

Table 13 - Test 7 Results for Fans 1 & 2

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.138	921801
4	2	0.044	3132027
6	1	1.43	88957
8	2	1.54	89486
10	1	1.67	76173
12	2	1.49	92489
14	1	1.6	79505
16	2	1.61	85596
18	1	1.78	71465
20	2	1.48	93114
22	1	1.59	80005
24	2	1.64	84030
26	1	1.53	83143
28	2	1.51	91264

Table 14 - Test 8 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	*%*
Fan #1	82508	5934	7.19
Fan #2	99711	1993	2.00

Table 15 - Average Flow and Deviation, Test 7

Average Last 4 Measurments			
	Flow	*Std Dev*	*%*
Fan #1	78530	4977	6.34
Fan #2	88501.10973	4372	4.94

Table 16 - Average Flow and Deviation, Test 8

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.158	805117
4	2	0.069	1997235
6	1	2.24	56790
8	2	2.69	51230
10	1	2.34	54363
12	2	2.82	48869
14	1	2.38	53449
16	2	2.5	55124
18	1	2.38	53449
20	2	2.59	53208
22	1	2.35	54131
24	2	2.54	54256
26	1	2.23	57044
28	2	2.56	53832

Table 17 - Test 9 Results for Fans 1 & 2

Time (min)	Fan Number	Concen (ppb)	Flow Rate (cfm)
2	1	0.291	437143
4	2	0.051	2702141
6	1	1.91	66601
8	2	2.62	52599
10	1	2.19	58086
12	2	2.07	66574
14	1	1.78	71465
16	2	1.87	73695
18	1	1.72	73958
20	2	2.05	67224
22	1	1.79	71066
24	2	1.9	72531
26	1	1.74	73108
28	2	2.08	66254

Table 18 - Test 10 Results for Fans 1 & 2

Average Last 4 Measurments			
	Flow	*Std Dev*	*%*
Fan #1	54518	1714	3.14
Fan #2	54104.7887	804	1.49

Table 19 - Average Flow and Deviation, Test 9

Average Last 4 Measurments			
	Flow	*Std Dev*	*%*
Fan #1	72400	1364	1.88
Fan #2	69926.07863	3731	5.34

Table 20 - Average Flow and Deviation, Test 10

D1.2 Solving the Power Law Equation by Minimizing RMS Error

The set of equations listed below is titled "Error Analysis," but this actually refers to minimizing the root mean square error produce by selecting the best fit C value for a given range of "n" values. This is explained in full detail in Section 6.2. The differential pressure measurements across the building floors are averaged and input into the P_xy variable. The x indicates the test run and the y is the floor corresponding to the recorded pressure. The actual outdoor air flow was determined in the orifice plate calibration and is designated Q_xact. The predicted airflow, Q_xpred, is the value which is being set equal to the actual airflow. Q_xpred is based on Equation 13 and uses the average pressure previously described. The solution is set to minimize the total error, Error_tot, for a given n value, by selecting C. The solutions to the test runs for the 10 August test date follows the equations. The USX Tower equations are computed on the same principles, but there are just more averaged pressures due to the increase in floors from 5 to 13.

D1.2.1a Solving for C and n - Equations (10 August)

"Error Analysis - Test Date: 10 August 1997"

"Test 1 - 10 August 1997"
P_149=(115.1+129.6+137.9)/3
P_150=(149.9+144.5+153.5)/3
P_151=(148.5+146.5+141.8)/3
P_152=(132.5+127+134.2)/3
P_153=(99.6+119.5+114.2)/3
P_154=(96.9+99+113)/3
P_155=(84.3+111.5+111.5)/3
P_156=(81.1+80.4+99)/3
P_157=(112.7+112.4+116.6)/3
P_158=(143.3+137.8+143)/3
P_159=(144+144.5+146.2)/3
P_160=(152.5+134.4+144.1)/3
P_161=(145+140.5+141)/3

Q_1act=222108

Q_1pred=C*((P_149^n)+(P_150^n)+(P_151^n)+(P_152^n)+(P_153^n)+(P_154^n)+(P_155^n)+(P_156^n)+(P_157^n)+(P_158^n)+(P_159^n)+(P_160^n)+(P_161^n))

Error_1=(Q_1act-Q_1pred)^2

"Test 2 - 10 August 1997"
P_249=(144.5+129.9+138.5)/3
P_250=(157.7+155.5+161.8)/3
P_251=(133.9+152.8+124.7)/3
P_252=248.8*(.52+.5+.51)/3

```
P_253=248.8*(.52+.51+.54)/3
P_254=248.8*(.53+.52+.55)/3
P_255=248.8*(.46+.44+.46)/3
P_256=(147.7+144.3+146.8)/3
P_257=(148.8+147.7+152)/3
P_258=(146.7+84.2+131.2)/3
P_259=(148.5+133+144)/3
P_260=(149+142+150)/3
P_261=(118+121+146)/3

Q_2act=242462

Q_2pred=C*((P_249^n)+(P_250^n)+(P_251^n)+(P_252^n)+(P_253^n)+(P_254^n)+(P_2
55^n)+(P_256^n)+(P_257^n)+(P_258^n)+(P_259^n)+(P_260^n)+(P_261^n))

Error_2=(Q_2act-Q_2pred)^2

"Test 3 - 10 August 1997"
P_349=(139.9+123.3+140.5)/3
P_350=(149.3+143.5+147.5)/3
P_351=(138.2+151.7+153.3)/3
P_352=248.8*(.45+.49+.5)/3
P_353=248.8*(.46+.52+.52)/3
P_354=248.8*(.48+.49+.52)/3
P_355=248.8*(.51+.51+.51)/3
P_356=(136.5+134.4+141)/3
P_357=(135.7+142.2+144.9)/3
P_358=(139.4+137.2+141)/3
P_359=(135+143+142.5)/3
P_360=(138.1+135.5+141)/3
P_361=(138+135+140)/3

Q_3act=229269

Q_3pred=C*((P_349^n)+(P_350^n)+(P_351^n)+(P_352^n)+(P_353^n)+(P_354^n)+(P_3
55^n)+(P_356^n)+(P_357^n)+(P_358^n)+(P_359^n)+(P_360^n)+(P_361^n))

Error_3=(Q_3act-Q_3pred)^2

"Test 4 - 10 August 1997"
P_449=(130.5+125.8+116.7)/3
P_450=(150.6+145.3+151.5)/3
P_451=(147.5+145.7+142.8)/3
P_452=248.8*(.47+.46+.49)/3
P_453=248.8*(.5+.48+.48)/3
P_454=248.8*(.5+.49+.48)/3
```

P_455=248.8*(.5+.52+.52)/3
P_456=(143.3+143.1+144.5)/3
P_457=(142.1+140.2+141.3)/3
P_458=(146+141+144.2)/3
P_459=(144+137+139)/3
P_460=(144+136+141)/3
P_461=(138+133+131)/3

Q_4act=232951

Q_4pred=C*((P_449^n)+(P_450^n)+(P_451^n)+(P_452^n)+(P_453^n)+(P_454^n)+(P_455^n)+(P_456^n)+(P_457^n)+(P_458^n)+(P_459^n)+(P_460^n)+(P_461^n))

Error_4=(Q_4act-Q_4pred)^2

"Test 5 - 10 August 1997"
P_549=(111.8+106.8+112.2)/3
P_550=(107.9+127.8+111.5)/3
P_551=(125.7+119.6+100.7)/3
P_552=248.8*(.41+.42+.46)/3
P_553=248.8*(.45+.45+.47)/3
P_554=248.8*(.45+.47+.47)/3
P_555=248.8*(.48+.47+.48)/3
P_556=(125+125+129.5)/3
P_557=(123.9+131.1+132.3)/3
P_558=(126.9+130.9+128)/3
P_559=(129+121.9+132.4)/3
P_560=(124.5+124.1+130.9)/3
P_561=(138+126+127.5)/3

Q_5act=201945

Q_5pred=C*((P_549^n)+(P_550^n)+(P_551^n)+(P_552^n)+(P_553^n)+(P_554^n)+(P_555^n)+(P_556^n)+(P_557^n)+(P_558^n)+(P_559^n)+(P_560^n)+(P_561^n))

Error_5=(Q_5act-Q_5pred)^2

"Test 6 - 10 August 1997"
P_649=(75.5+64+81.7)/3
P_650=(78.9+79.9+77.9)/3
P_651=(80.7+74.4+80.9)/3
P_652=248.8*(.44+.43+.44)/3
P_653=248.8*(.46+.44+.46)/3
P_654=248.8*(.47+.43+.47)/3
P_655=248.8*(.46+.46+.47)/3
P_656=(129.8+118.1+133.2)/3

P_657=(131.3+128.2+127.1)/3
P_658=(129.6+125+133)/3
P_659=(128+120+132)/3
P_660=(128.2+120+125.2)/3
P_661=(119.1+120.1+123)/3

Q_6act=201628

Q_6pred=C*((P_649^n)+(P_650^n)+(P_651^n)+(P_652^n)+(P_653^n)+(P_654^n)+(P_655^n)+(P_656^n)+(P_657^n)+(P_658^n)+(P_659^n)+(P_660^n)+(P_661^n))

Error_6=(Q_6act-Q_6pred)^2

"Test 7 - 10 August 1997"
P_749=(69.8+69.8+71.8)/3
P_750=(74.5+68.9+77.8)/3
P_751=(77.9+74.9+75.7)/3
P_752=248.8*(.42+.38+.43)/3
P_753=248.8*(.45+.42+.44)/3
P_754=248.8*(.45+.41+.47)/3
P_755=248.8*(.46+.44+.46)/3
P_756=(117.4+114.7+117.5)/3
P_757=(122.6+114.8+114.7)/3
P_758=(131.7+123.9+126.1)/3
P_759=(120.7+112.2+121.4)/3
P_760=(126.4+119+116)/3
P_761=(121.6+113+122.2)/3

Q_7act=182219

Q_7pred=C*((P_749^n)+(P_750^n)+(P_751^n)+(P_752^n)+(P_753^n)+(P_754^n)+(P_755^n)+(P_756^n)+(P_757^n)+(P_758^n)+(P_759^n)+(P_760^n)+(P_761^n))

Error_7=(Q_7act-Q_7pred)^2

"Test 8 - 10 August 1997"
P_849=(81.9+80.9+115.1)/3
P_850=(116.3+100.3+110.2)/3
P_851=(109.9+92.9+119)/3
P_852=248.8*(.37+.34+.38)/3
P_853=248.8*(.4+.36+.39)/3
P_854=248.8*(.42+.36+.39)/3
P_855=248.8*(.43+.37+.45)/3
P_856=(99+98.1+102.1)/3
P_857=(107.6+96.5+111.5)/3
P_858=(119.9+102.5+107.9)/3

P_859=(110.8+103.7+92.01)/3
P_860=(102.3+93.2+103.1)/3
P_861=(106.7+91+109.8)/3

Q_8act=167031

Q_8pred=C*((P_849^n)+(P_850^n)+(P_851^n)+(P_852^n)+(P_853^n)+(P_854^n)+(P_855^n)+(P_856^n)+(P_857^n)+(P_858^n)+(P_859^n)+(P_860^n)+(P_861^n))

Error_8=(Q_8act-Q_8pred)^2

"Test 9 - 10 August 1997"
P_949=(66.4+80+75.2)/3
P_950=(94.9+85.9+96.9)/3
P_951=(96.5+77.6+95.9)/3
P_952=248.8*(.33+.32+.33)/3
P_953=248.8*(.34+.32+.35)/3
P_954=248.8*(.35+.31+.35)/3
P_955=248.8*(.34+.3+.34)/3
P_956=(93.6+89.1+90.9)/3
P_957=(95.5+92.3+95.5)/3
P_958=(97.8+87.9+95.4)/3
P_959=(84.56+81.16+88.48)/3
P_960=(92.17+81.71+92.01)/3
P_961=(93.23+80.05+92.53)/3

Q_9act=108623

Q_9pred=C*((P_949^n)+(P_950^n)+(P_951^n)+(P_952^n)+(P_953^n)+(P_954^n)+(P_955^n)+(P_956^n)+(P_957^n)+(P_958^n)+(P_959^n)+(P_960^n)+(P_961^n))

Error_9=(Q_9act-Q_9pred)^2

"Test 10 - 10 August 1997"
P_1049=(91.9+84.9+98.4)/3
P_1050=(91.3+89.9+99.9)/3
P_1051=(93.5+79.9+97.1)/3
P_1052=248.8*(.32+.3+.32)/3
P_1053=248.8*(.34+.31+.35)/3
P_1054=248.8*(.34+.3+.32)/3
P_1055=248.8*(.33+.31+.34)/3
P_1056=(86.6+94.6+103.9)/3
P_1057=(90.6+70.1+85.7)/3
P_1058=(92.2+88.6+92.6)/3
P_1059=(100.4+70.89+101.2)/3
P_1060=(87.75+75.35+87.35)/3

P_1061=(90.41+75.64+87.31)/3

Q_10act=142362

Q_10pred=C*((P_1049^n)+(P_1050^n)+(P_1051^n)+(P_1052^n)+(P_1053^n)+(P_1054^n)+(P_1055^n)+(P_1056^n)+(P_1057^n)+(P_1058^n)+(P_1059^n)+(P_1060^n)+(P_1061^n))

Error_10=(Q_10act-Q_10pred)^2

"Total Error"

RMSErr_Tot=((Error_1+Error_2+Error_3+Error_4+Error_5+Error_6+Error_7+Error_8+Error_9+Error_10)/10)^.5

D1.2.1b Solving for C and n - Solutions (10 August)

n	C	Total Error
0.40	2261.9	29020
0.42	2057.9	28442
0.44	1872.3	27866
0.46	1703.4	27293
0.48	1549.6	26724
0.50	1409.7	26158
0.52	1282.4	25596
0.54	1166.5	25037
0.56	1061.0	24483
0.58	965.1	23932
0.60	877.8	23386
0.62	798.4	22844
0.64	726.1	22308
0.66	660.3	21776
0.68	600.5	21250
0.70	546.1	20730
0.72	496.6	20216
0.74	451.6	19709
0.76	410.6	19208
0.78	373.3	18715
0.80	339.4	18229
0.82	308.6	17753
0.84	280.6	17284
0.86	255.1	16826
0.88	231.9	16378
0.90	210.8	15940
0.92	191.6	15515
0.94	174.2	15102
0.96	158.4	14702
0.98	143.9	14316
1.00	130.8	13946
1.02	118.9	13593
1.04	108.1	13256
1.06	98.2	12939
1.08	89.3	12641
1.10	81.1	12364
1.12	73.7	12109
1.14	67.0	11878
1.16	60.9	11672
1.18	55.3	11491

n	C	Total Error
1.20	50.3	11336
1.22	45.7	11209
1.24	41.5	11110
1.26	37.7	11040
1.28	34.3	10998
1.30	31.1	10986
1.32	28.3	11002
1.34	25.7	11046
1.36	23.3	11118
1.38	21.2	11217
1.40	19.3	11341
1.42	17.5	11491
1.44	15.9	11663
1.46	14.4	11859
1.48	13.1	12075
1.50	11.9	12310
1.52	10.8	12564
1.54	9.8	12834
1.56	8.9	13120
1.58	8.1	13420
1.60	7.4	13734
1.62	6.7	14059
1.64	6.1	14396
1.66	5.5	14742
1.68	5.0	15098
1.70	4.5	15461
1.72	4.1	15833
1.74	3.7	16211
1.76	3.4	16595
1.78	3.1	16984
1.80	2.8	17379
1.82	2.5	17778
1.84	2.3	18181
1.86	2.1	18588
1.88	1.9	18997
1.90	1.7	19410
1.92	1.6	19825
1.94	1.4	20242
1.96	1.3	20661
1.98	1.2	21081

Table D21 - Determining C and n by Minimizing Total Error (10 August 1997)

Appendix E

Error Analysis Derivatives

Appendix E

Tracer Gas Flow Rate Error Analysis Derivation

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Tracer Gas Flow Rate Error Analysis Derivation

The general arrangement of a tracer gas system to measure the flow rate of outdoor air into an air-handling unit is shown in Figure E1. A tracer source of strength S is injected into the return air stream. Concentrations C_{Ret1}, C_{Ret2}, and C_{Sup} are measured at the indicated locations.

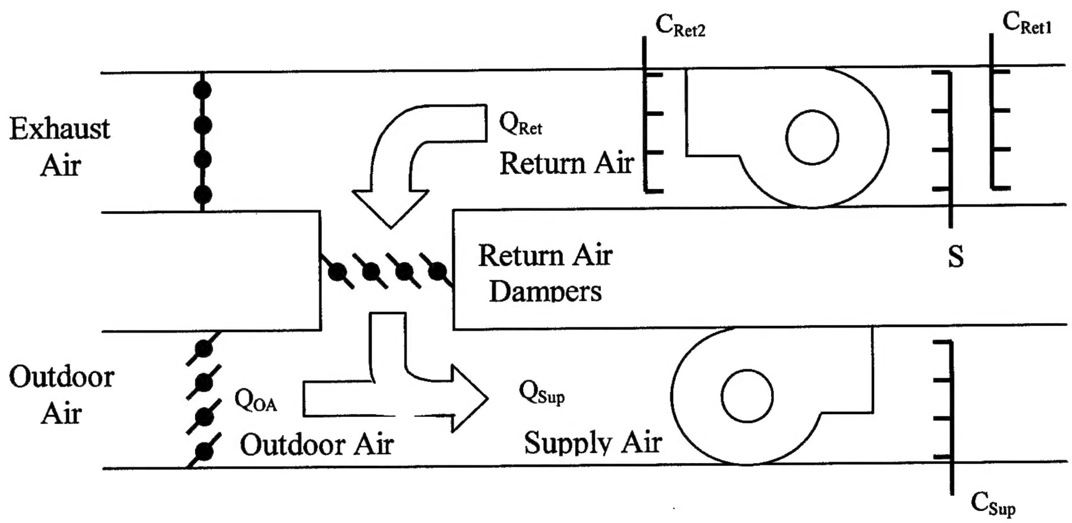

Figure E1 – Air-Handler OA Flow Rate Measurement - Tracer Gas with Return Air

Assuming that the source strength and three concentrations are known, the three unknown airflow rates Q_{OA}, Q_{Ret}, and Q_{Sup} are defined by the following relations:

$$Q_{Ret} = \frac{S}{(C_{Ret2} - C_{Ret1})} \tag{4.4}$$

$$Q_{Sup} = Q_{Ret}\left(\frac{C_{Ret2}}{C_{Sup}}\right) \tag{4.5}$$

$$Q_{OA} = Q_{Sup} - Q_{Ret} \tag{4.6}$$

Equations 4.4 through 4.5 may be solved simultaneously to give an expression for Q_{OA} in terms of S, C_{Ret1}, C_{Ret2}, and C_{Sup}.

First, eliminate Q_{Sup} from Equation 4.6 by substitution from Equation 4.5

$$Q_{OA} = Q_{Ret}\left(\frac{C_{Ret2}}{C_{Sup}} - 1\right)$$

$$= Q_{Ret}\left(\frac{C_{Ret2} - C_{Sup}}{C_{Sup}}\right) \qquad \text{(E1)}$$

Now, eliminate Q_{Ret} from Equation E1 by substitution from Equation 4.4 to obtain the desired expression for Q_{OA}:

$$Q_{OA} = \frac{S}{C_{Ret2} - C_{Ret1}}\left(\frac{C_{Ret2} - C_{Sup}}{C_{Sup}}\right)$$

$$= \frac{S}{C_{Sup}}\left(\frac{C_{Ret2} - C_{Sup}}{C_{Ret2} - C_{Ret1}}\right) \qquad \text{(E2, 4.7)}$$

From E2, derivatives of Q_{OA} with respect to each of the measured variables are calculated as follows:

Differentiating Q_{OA} with respect to S,

$$\frac{\partial Q_{OA}}{\partial S} = \frac{1}{C_{Sup}}\left(\frac{C_{Ret2} - C_{Sup}}{C_{Ret2} - C_{Ret1}}\right) \qquad \text{(E3)}$$

Differentiating Q_{OA} with respect to C_{Sup},

$$\frac{\partial Q_{OA}}{\partial C_{Sup}} = -\frac{S}{C_{Sup}^2}\left(\frac{C_{Ret2} - C_{Sup}}{C_{Ret2} - C_{Ret1}}\right) - \frac{S}{C_{Sup}}\left(\frac{1}{C_{Ret2} - C_{Ret1}}\right)$$

$$= -\frac{S\,C_{Ret2}}{C_{Sup}^2\left(C_{Ret2} - C_{Ret1}\right)} \qquad \text{(E4)}$$

Differentiating Q_{OA} with respect to C_{Ret1},

$$\frac{\partial Q_{OA}}{\partial C_{Ret1}} = \frac{S\left(C_{Ret2} - C_{Sup}\right)}{C_{Sup}\left(C_{Ret2} - C_{Ret1}\right)^2} \tag{E5}$$

Finally, differentiating Q_{OA} with respect to C_{Ret2},

$$\frac{\partial Q_{OA}}{\partial C_{Ret2}} = \frac{S}{C_{Sup}}\left(\frac{1}{C_{Ret2} - C_{Ret1}} - \frac{C_{Ret2} - C_{Sup}}{(C_{Ret2} - C_{Ret1})^2}\right)$$

$$= -\frac{S\left(C_{Ret1} - C_{Sup}\right)}{C_{Sup}\left(C_{Ret2} - C_{Ret1}\right)^2} \tag{E6}$$

Making use of derivatives E3 through E6 in Equation 8.4, the total uncertainty in the flow rate can be estimated.